Exploring Geothermal Application in Flooded Underground Mines with an Analogue Model Mine

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Abstract

Geothermal use of flooded underground mines is gaining popularity, particularly utilising warm mine water for heating purposes. A current example is the former colliery Dannenbaum in Bochum, Germany. The "Agricola Model Mine" in Pretoria, South Africa, was set up to replicate conditions at the Dannenbaum colliery. With this model mine it was possible to monitor parameters like temperature, electrical conductivity and change of tracer concentration while warm, mineralised mine water was reinjected in the upper mine water body and caused breakdown of the existing density stratification. These findings indicate that a change in the water chemistry, due to geothermal pumping, is possible.

Keywords: Mine water, analogue model, numerical modelling, stratification, geothermal, mine water heat

Introduction

In recent years, there has been an increase in the reuse of former mine sites for various purposes, including flooded mines. This trend recognises the potential of mine water as a valuable resource. Two main applications have emerged: the extraction of raw materials from mine water and the geothermal use of mine water. Typically, warm mine water is utilised for heating, although cooling or mine thermal energy storage (MTES) is possible as well (Banks *et al.* 2017; Grab *et al.* 2018; Hahn 2024b; Walls *et al.* 2021)(Fig. 1). Understanding the hydrodynamic processes within flooded underground mines is crucial for all types of geothermal utilisation. Density stratification, defined as the presence of water bodies with different physico-chemical properties within the flooded mines, is one of these processes (Mugova and Wolkersdorfer 2022; 2025). It has been shown, that density stratification can be disturbed or caused to breakdown by the use of pumps, ultimately leading to a deterioration of water quality. The aim of this paper is to use analogue modelling to investigate whether geothermal pumping activities could influence density stratification and discharge water quality.

Methods

In order to investigate the potential stratification breakdown in a flooded mine, it is essential to establish baseline parameters that closely resemble real-world conditions, thereby enabling the results to be applicable to other mining sites. For this reason, an applied analog model was based on the former Dannenbaum colliery in Bochum, Germany.

The colliery is an old mine site, where coal extraction began in the 14th century and transitioned to underground mining in 1843, with shaft depths exceeding 600 m. In 1963, the mine was closed following the amalgamation of several neighbouring collieries. Today, the area, which later housed the Opel car factories, is being economically developed under the name Mark 51°7. With the objective of supplying a sustainable geothermal heat and cooling system to

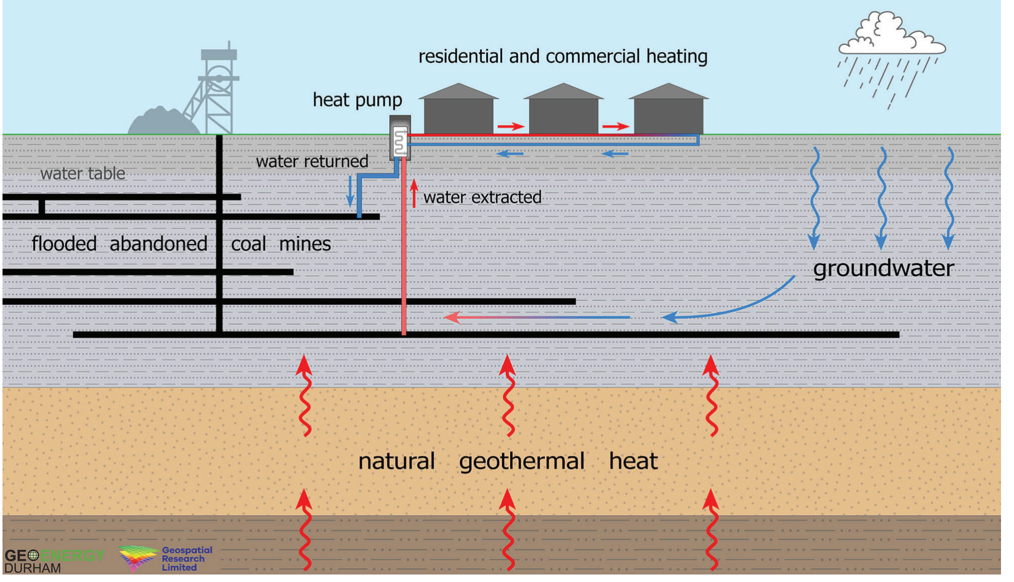

Figure 1 Schematic overview on how to utilise mine water for geothermal heating (from Geospatial Research Ltd. 2025).

Mark 51°7, two directional wells (GT1 and GT2, Fig. 2) have been drilled into the mine workings (Hahn 2024a). The long-term vision for the flooded mine is to utilise it for geothermal heating and cooling in a LT-MTES (low temperature mine thermal energy storage). However, it should be noted that these associated pumping activities will affect the hydraulic system. Current observations indicate the existence of density stratification within the flooded mine, characterised by the presence of at least two distinct water bodies: an upper CF (cold-fresh) water body with a temperature of 16.4 °C and an electrical conductivity of 1.7 mS/cm, and a lower WM (warm mineralised) water body with a temperature of 26.0 °C and an electrical conductivity of 10.4 mS/cm. This study will investigate whether the stratification is affected by pumping activities and what implications this may have on the discharged water quality.

The Agricola Model Mine (AMM) is a scaled-down reconstruction of a flooded underground mine, measuring 6 × 4 m. Since 2021, it has been operational at Tshwane University of Technology (TUT) in Pretoria, South Africa. Designed to replicate conditions in a flooded underground mine, the model utilises dimensions scaled-down according to the Reynolds number. With depths of 65 cm, 145 cm, 225 cm, and 305 cm, and a diameter of 90 mm, the four horizontal levels are connected to four shafts. Constructed from insulated, transparent PVC tubes, the AMM can accommodate a total water volume of 153 L. To simulate rainwater inflow, a peristaltic pump continuously supplied water to the upper part of the AMM, while natural discharge is replicated at the outflow of shaft #1. A total of 36 sampling ports are incorporated into the model for comprehensive water monitoring and sampling. Heating foils are placed in the sumps of all four shafts in order to create geothermal gradients, achieving maximum water temperatures of 42 °C (Molaba 2022; Mugova *et al.* 2024).

All four shafts and four horizontal levels were incorporated into the experimental set-up to ensure a representation of the Dannenbaum colliery. Initially, mine pool conditions with density stratification were established, using parameters that closely imitate those of the Dannenbaum site. After 10 days of undisturbed conditions, different fluorescent tracers were injected into the upper CF water body (above level 145) and WM water body

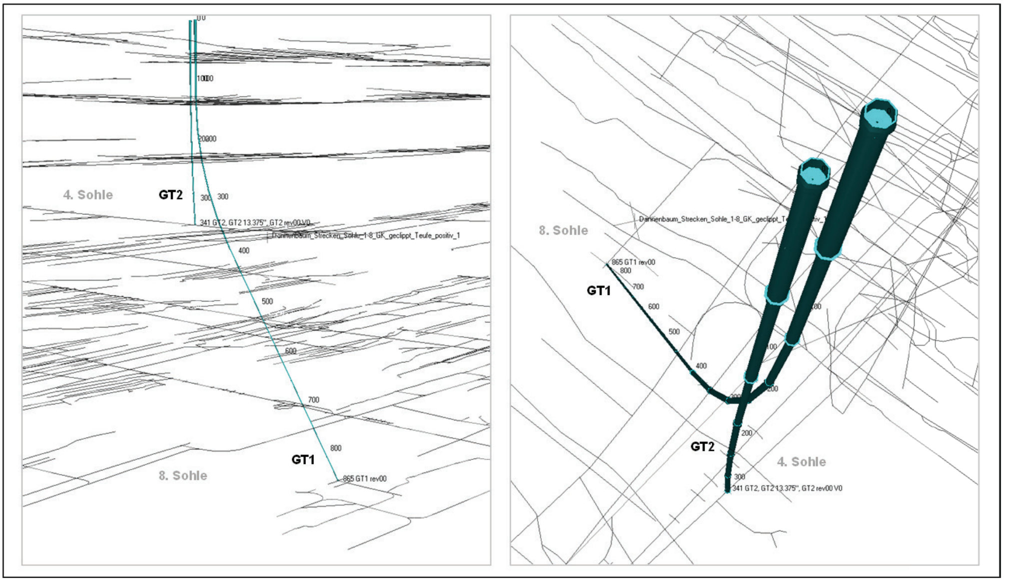

Figure 2 *Directional wells GT1 & GT2 at Dannenbaum colliery (Hahn 2024a).*

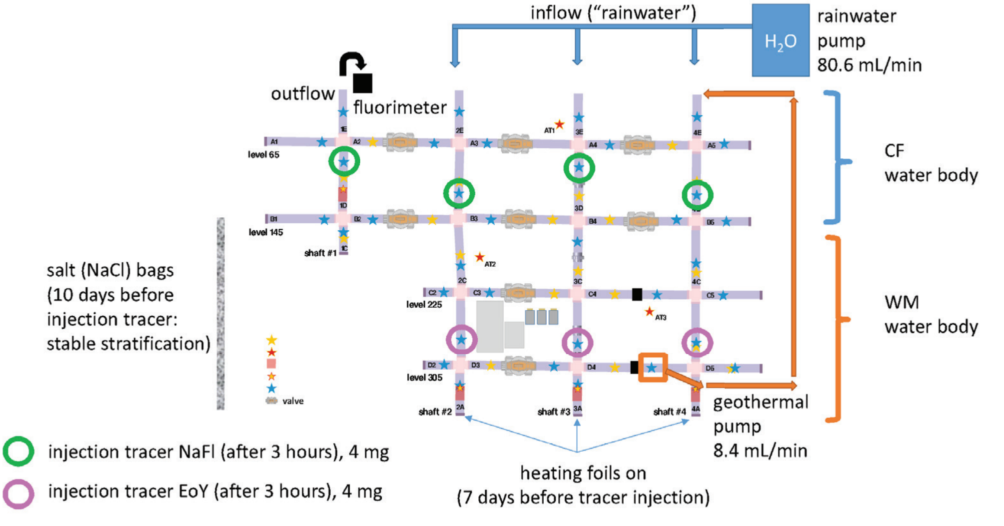

Figure 3 *AMM set-up of the experiment with tracers Sodium Fluorescein (NaFl) and EosinY (EoY).*

(below level 145). Subsequently, analogue to geothermal pumping activities, warm, higher mineralised mine water was extracted from the WM water body and reinjected into the CF water body (Fig. 2). Throughout a 49-day monitoring period, changes in water parameters were tracked using 10 electrical conductivity and temperature probes, as well as through continuous tracer concentration measurements.

Results and Discussion

A clear separation was observed in the temperature data when the heating foils were activated, indicating a lower water body with temperatures ranging from 22.8 to 23.3 °C and an upper water body with temperatures between 17.6 and 18.7 °C. However, this stratification was disrupted by the extraction of warm water from the WM water body and its reinjection into the CF water body.

Following the activation of the geothermal pump on day 7.0, a rise in temperature was observed in the WM water body until day 7.6, after which a rapid decline was evident in sections 2C, 3C, and 4C within approximately 14.4 hours. By 19.2 to 33.4 hours post geothermal pumping, the temperatures in these sections equalled those in the CF water body, indicating a swift mixing of the upper WM water body. Sections 2B and 4B showed a similar trend, initially rising to a maximum of 24.9 °C on day 8.4 before mixing with cooler water, which led to a temperature drop. The mixing process took longer in the lower WM compared to the upper sections. In the CF water body, the introduction of warm water resulted in a uniform temperature increase across all sections. By day 10.8, 92.9 hours after the geothermal pump was activated, complete mixing occurred, leading to a temperature range of 21.1 to 21.5 °C. There was no recovery of stratification observed for the remainder of the experiment, and post-breakdown temperatures fluctuated between 19.9 and 25.3 °C, primarily influenced by changes in room temperature and the temperature of the incoming tap water (Fig. 3). A similar mixing process could be determined from the electrical conductivity data.

Continuous monitoring of sodium fluorescein (NaFl) concentrations at outflow shaft #1 revealed three distinct peaks. The first peak resulted from flushing NaFl added before rainwater influx, while the second, higher peak came from additional NaFl introduced into the CF water body, leading to a quick tracer flush. The third peak around day 16 is unexplained, likely due to disturbances from geothermal pumping. Following the initial sodium fluoride (NaF) injection, even distribution was achieved within a few days, with minimal detection in sump section 1C. However, the presence of NaFl in the WM water body was minimal, with an average of 0.85 µg/L after three days, in comparison to 17.96 µg/L in the CF water body. Rainwater further flushed NaFl in the CF water body out, while concentrations in the WM water body remained stable. Notably, the geothermal pump had only minimal effect on NaFl concentrations in the CF water body. Following the injection of EoY dye tracer in the WM water body, the tracer was evenly distributed in the WM until the geothermal pump was switched on, with an average concentration of 46.72 µg/L recorded after 6.9 days. Subsequent to pump activation, EoY concentrations in the WM

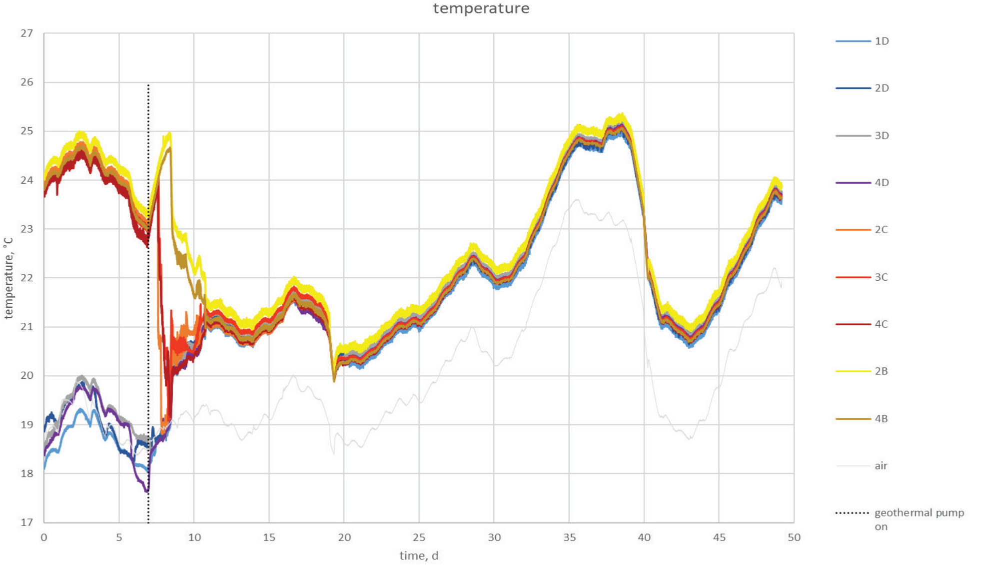

Figure 4 Temperature curve before and after the geothermal pump was switched on (dotted line) with probes above level 145 (1D, 2D, 3D, 4D) and probes below level 145 (2C, 3C, 4C, 2B, 4B).

underwent a substantial decrease (averaging 0.80 µg/L by day 49), predominantly in sections directly beneath the CF, due to dilution from CF water. Geothermal pumping also resulted in the transfer of water from the WM to the CF water body, thereby raising EoY concentrations in the CF water body. With exception of section 2E, EoY rapidly disseminated throughout the CF. Within 24 hours after pump activation, the average EoY concentration in the CF water body was 8.27 µg/L. However, it decreased to 1.41 µg/L by day 49 due to influx of fresh water.

Overall, the geothermal pumps, i.e. the extraction of water from the WM water body and its reinjection into the CF water body, caused rapid mixing. This resulted in a mixed water body. Larger temperature fluctuations occurred in the mixed water body due to lab conditions. In contrast, the electrical conductivity, which can be seen as an indicator of mine water mineralisation, decreased over time, caused by the permanent supply of fresh water and the forced flow from pumping. The mineralised water was flushed out over time, whilst "geothermal" heat by the heating foils was supplied continuously.

Conclusions

Through analogue modelling in the AMM, it was possible to understand the conditions in the flooded Dannenbaum colliery. These include the presence of density stratification and the future withdrawal and injection of water for geothermal use from the lower WM water body and the upper CF water body. Based on the AMM results, it can be assumed that the pumping activities in the Dannenbaum colliery will cause mixing of the currently existing water bodies. Due to the high electrical conductivity in the WM water body, an increase in mineralisation is to be expected when the WM water body is reinjected into the CF water body. This change in chemistry must be taken into account when configuring the heat exchangers. Temporal predictions regarding a potential stratification breakdown within the flooded mine remain uncertain at this time. Water is only used from a small area of the Dannenbaum mine workings (394 km in total), suggesting that it is negligible in relation to the overall hydraulic system (Prinz Regent colliery with 288 km and Friedlicher Nachbar colliery with 320 km of mine workings additionally to Dannenbaum). However, geothermal pumping must not be mistaken with mine dewatering pumping activities. Mine water drainage takes place at the former colliery Friedlicher Nachbar, about 7 km away und connected via several other abandoned coal mines. The water of all surrounding former mines is pumped centrally at this site. Despite the potential for increased mine water mineralisation directly at the Dannenbaum mine, dilution effects over the extended inflow distance suggest that no detrimental changes in mine water quality at Friedlicher Nachbar are to be expected. Once the geothermal pump at the Dannenbaum mine (Mark 51°7) commences operation, a monitoring programme for water quality should be initiated, encompassing both the immediate vicinity of the mine and the Friedlicher Nachbar site. In addition, numerical modelling with SPRING is planned to compare both the AMM results and the real data available so far. Having the possibility to model both, flooding scenarios and utilisation of mine water in an analogue way, provides a good opportunity to better understand the complex hydraulic system of a flooded mine and to support mine water management decision-making.

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