Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Unlocking the Potential of Abandoned Coal Mines for Thermal Energy Storage: A Stepwise Modelling Approach

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Keywords: mine water, thermal energy storage, thermo-hydraulic modelling, SPRING, Ruhr area

INTRODUCTION

The ongoing energy transition in Europe calls for innovative approaches to seasonal heat storage and the reuse of existing subsurface infrastructure. Flooded coal mines offer enormous thermal capacities and existing access through shafts and galleries, making them promising candidates for mine-water based ATES systems (Hahn et al., 2022). However, the safe and sustainable operation of such systems requires a detailed understanding of the hydrogeological and thermal processes within the mine environment, including interactions between mine voids, fractures, and surrounding aquifers.

The WINZER project, conducted by a consortium of research institutions and industrial partners, addresses these challenges by developing a transferable methodology for site assessment, monitoring, and modelling of mine-based heat storage systems. Within this framework, thermo-hydraulic simulations play a key role in predicting system performance, ensuring operational safety, and improving the cost-effectiveness of future installations.

To evaluate the effects of the ATES system on the surrounding aquifer, numerical models are employed to simulate groundwater flow and heat transport. These models also assess density-dependent processes, the physical environment and the impact of various pumping scenarios. A stepwise modelling approach has been developed to address the complex geological and mining conditions that are typical of the Ruhr region in Germany. This approach provides a basis for understanding groundwater behaviour and forms the foundation for the numerical simulations.

1 PROJECT SITES AND OBJECTIVES

To account for the wide range of geological, hydrogeological, and mining conditions found in the Ruhr region of Germany, three representative sites are investigated within the project:

- A near-surface isolated site, representing small-scale systems with limited hydraulic connection.
- A deep mine complex connected to the central dewatering system, illustrating strongly coupled mine-aquifer systems.
- A disused underground factory, characterized by large underground cavities and complex geometry.

At the time of writing, work on the near-surface site has been largely completed, while the studies on the deep mine complex and the underground factory are ongoing. Each site contributes specific insights into the hydraulic and thermal behavior of different mining environments and supports the development of transferable design and management concepts.

2 NUMERICAL MODELLING APPROACH

The numerical simulations are carried out using the 3D groundwater flow and transport code SPRING, developed by delta h, Germany (König et al., 2025). SPRING employs a finite-element formulation to solve the coupled equations for groundwater flow and solute or heat transport. The software allows the simulation of both steady-state and transient conditions, density-dependent flow, as well as heat convection and conduction. Complex geological geometries, irregular layer thicknesses, and pinching-out stratigraphy can be represented accurately within the model domain.

Given the complex geological and mining setting of the Ruhr area, a stepwise, multi-scale modelling concept was developed (Figure 1).

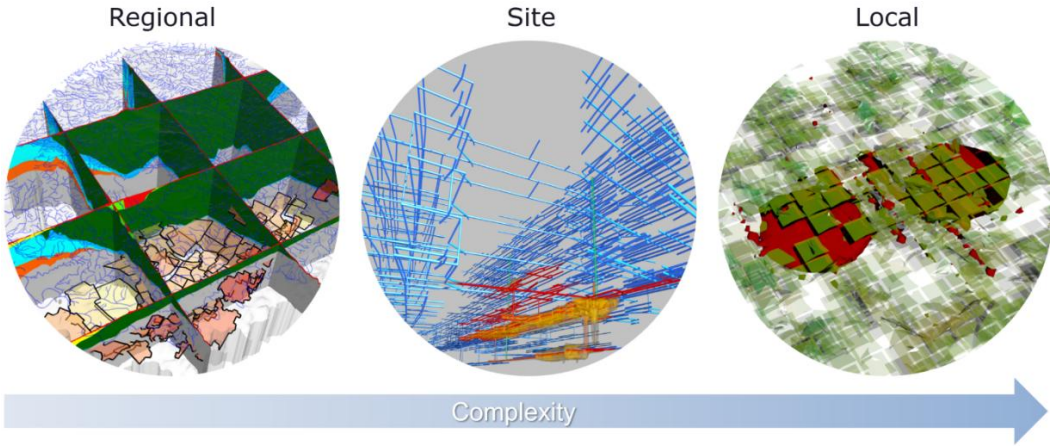


Figure 1. Schematic representation of the stepwise modelling approach for mine-water based thermal energy storage (MTES), showing the hierarchical transition from regional hydrogeological modelling to detailed local thermo-hydraulic simulations.

This framework provides a systematic pathway from regional to local detail, ensuring both computational efficiency and conceptual consistency across scales. It serves as the foundation for understanding the groundwater regime and for performing predictive heat transport simulations.

3 MULTI-SCALE MODELLING FRAMEWORK

3.1 Regional Scale (> 10,000 km^2)

At the largest scale, the model encompasses the overall geological and hydrogeological framework of the Ruhr basin. It represents the main aquifer systems, the distribution of mining areas, and the historic and current dewatering infrastructure (Figure 2).

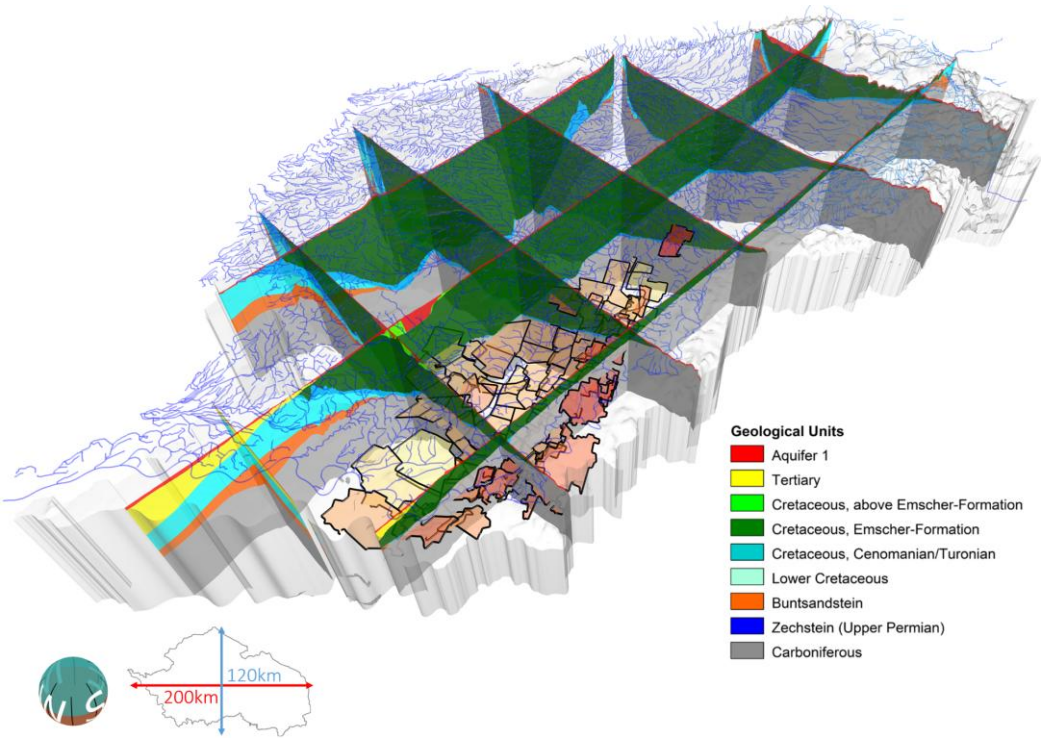


Figure 2. Regional-scale model representing the geological framework, aquifer systems, and mining areas grouped into water provinces (horizontal surfaces colored by water level from yellow = low to red = high).

The regional model simulates the long-term development of groundwater levels during and after mine closure, capturing the dewatering and rebound processes associated with the cessation of pumping.

Calibration is performed using historical dewatering rates, recorded mine water levels, and long-term groundwater observations. The regional model provides the hydraulic boundary conditions and flux information for the nested site-scale models.

3.2 Site Scale (~ 30 km^2)

The site scale, the numerical models focus on the immediate surroundings of each pilot location, capturing the key hydraulic and thermal processes that control the exchange between the flooded mine system and the adjacent aquifer. This intermediate model scale acts as a bridge between the large-scale regional framework and the high-resolution local models, allowing for a more detailed representation of mine geometry and geological heterogeneity while maintaining computational efficiency. The site-scale domain includes a geometrically explicit depiction of the mine layout, including shafts, galleries, and major connecting drifts, as well as the surrounding geological units such as overlying aquifers, aquitards, and the confining Carboniferous strata. This level of detail enables the model to capture flow paths both within the mine workings and through the adjacent rock formations, thereby allowing an integrated analysis of mine–aquifer interactions.

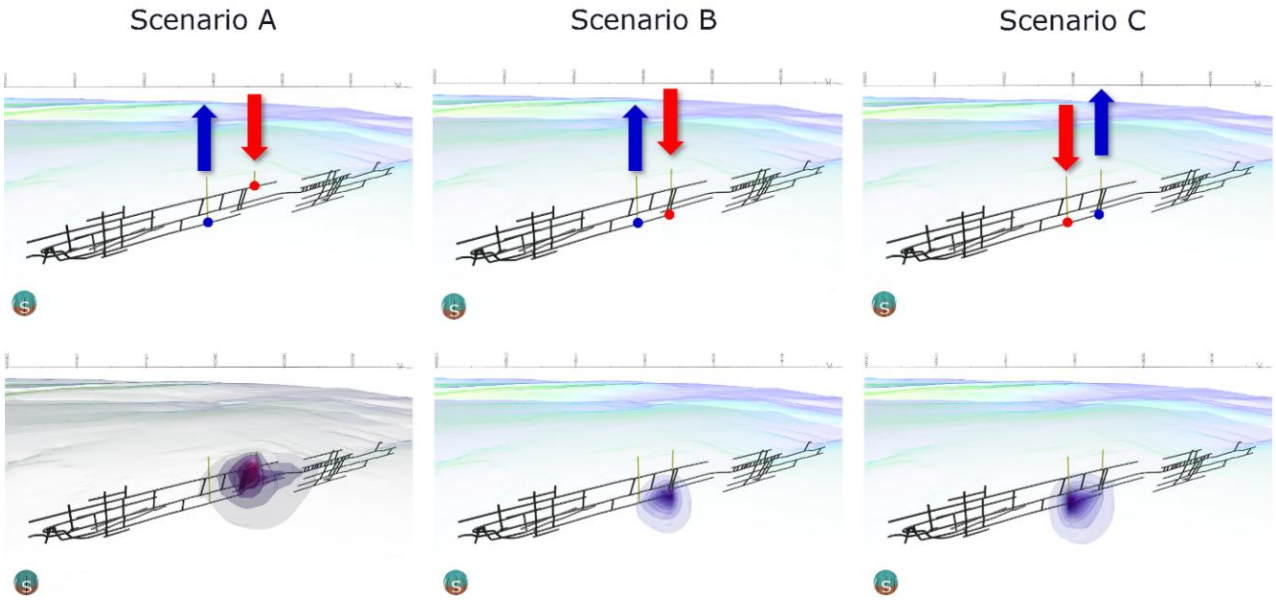


Figure 3. Simulated steady-state temperature distribution for multiple operating scenarios at the near-surface mining site. Arrows indicate injection (red) and production (blue) locations.

Coupling between the regional and site-scale domains is achieved through Neumann boundary conditions, ensuring mass-conserving flux transfer and consistency with large-scale groundwater flow patterns influenced by historic dewatering and rebound processes. The site-scale model thus refines hydraulic and thermal conditions derived from the regional simulations. At this level, the modelling investigates hydraulic connectivity, thermal plume dispersion, and the interaction between injection and production wells under various operational scenarios. Variable-density flow and temperature-dependent fluid properties are implemented to capture buoyancy effects and density-driven flow within the flooded mine workings (Figure 3).

By resolving the mine geometry and key geological features, the site-scale model provides essential insight into the spatial extent of thermal and hydraulic influence zones and delivers realistic boundary conditions for the subsequent local-scale thermo-hydraulic simulations.

3.3 Local Scale (< 1 km^2)

At the smallest scale, local models resolve detailed processes in the vicinity of specific shafts, galleries, or fractures. The Carboniferous rock at the study sites is highly fractured, and groundwater flow is mainly controlled by these discontinuities. Therefore, a discrete fracture–matrix approach is applied (König, 1998). This allows for high-resolution simulation of advective flow, conductive and convective heat transport, and localized mixing between fractures and rock matrix.

The local models are used to investigate the influence of fracture density, aperture, and connectivity on heat transfer efficiency and to estimate the thermal recovery ratio of the system (Figure 4). They also allow assessment of residual mine void volumes and alternative operation modes, such as seasonal versus

continuous cycling. Once calibrated and validated, relevant parameters derived at this scale are transferred upward to the site model, ensuring consistent representation of sub-grid processes.

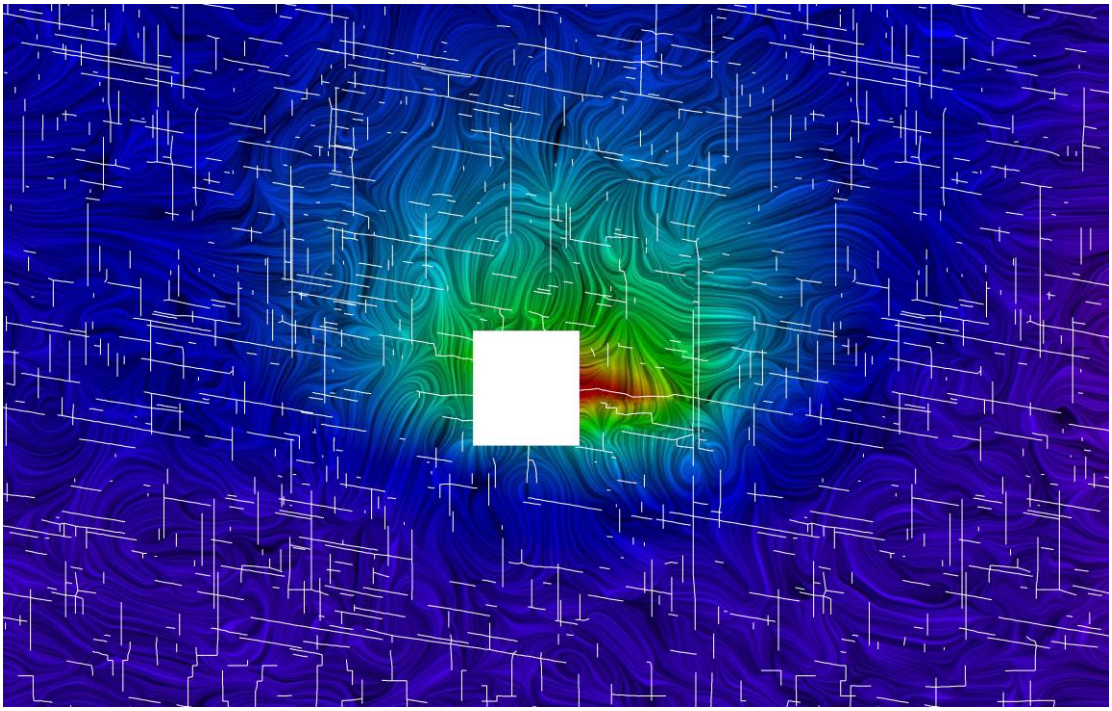


Figure 4. High-resolution 2D vertical model oriented perpendicular to a mining cavity (white rectangle). The simulation examines the impact of a discrete fracture–matrix system (white lines) on the thermal field and heat transfer processes in the surrounding rock close to the mine workings.

4 RESULTS AND DISCUSSION

Preliminary modelling results demonstrate that the stepwise, nested approach is effective for describing the complex thermo-hydraulic interactions within flooded mine systems. The regional model successfully reproduces historical dewatering and rebound dynamics, while the site-scale model captures localized flow and temperature distributions influenced by mine geometry.

Simulations reveal that the mine infrastructure significantly enhances hydraulic conductivity and thermal storage capacity, but also introduces anisotropic flow patterns and preferential pathways that can affect thermal dispersion. Variable-density simulations indicate that buoyancy effects may influence the stability of the thermal plume during injection and storage phases, especially under high temperature contrasts.

The local fracture–matrix models provide critical insights into the small-scale heat transfer processes that govern the overall system efficiency. They show that even small fracture zones can substantially improve the heat exchange between mine water and the surrounding rock, thereby increasing the effective storage capacity. These findings guide the optimization of well placement, pumping schedules, and operational strategies.

5 CONCLUSIONS

The WINZER project establishes a comprehensive modelling framework for assessing and designing mine-water based heat storage systems. The multi-scale approach, implemented using the SPRING code, bridges the gap between large-scale groundwater dynamics and small-scale thermo-hydraulic processes. This methodology enables robust predictions of system performance, facilitates risk assessment, and supports the transfer of knowledge to other post-mining regions.

The stepwise modelling concept has already proven transferable and is being applied to additional sites within the Ruhr area. Together with ongoing monitoring activities, it contributes to the long-term goal of developing safe, accepted, and economically viable underground heat storage solutions that transform abandoned mining infrastructure into a valuable asset for the energy transition.

Acknowledgements

The WINZER project is funded by The Federal Ministry of Education and Research (Germany).

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