Articles

Geological factors in the sustainable management of mine water heating, cooling and thermal storage resources in the UK

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Abstract: Re-use of the UK's coal mine water heating, cooling and thermal storage resource is increasing in scale and the number of schemes. The upward trajectory requires 3D planning, regulation and licensing to manage sustainable deployment. We review geological factors controlling thermal and flow processes in the anthropogenically-altered subsurface, critical for resource management with multiple users of the same space. Potential interactions of mine water geothermal schemes with the wider environment are also summarized, leading towards concepts of 3D mine water thermal blocks, protection zones, or management strategies integrating heating, cooling and storage demands.

Factors such as the magnitude, extent and timescale of thermal processes to underpin management approaches are poorly quantified by data measured at-scale under varying pumping rates and thermal loads. We demonstrate early insights of how two infrastructures, the UK Geoenergy Observatory in Glasgow and the Coal Authority's Mine Water Heat Living Lab in Gateshead, can measure and monitor heat-flow processes in real world settings to provide an evidence base. For example, a thermal storage test at Glasgow showed rapid temperature changes in the rock and mine workings at the re-injection borehole and indicated an influence of lithologically-controlled transmissivity and thermal conductivity on temperature dissipation and recovery.

Supplementary material: Two spreadsheets of data as plotted on Figure 5 are available at https://doi.org/10.6084/m9.figshare.c.7397933

Re-use of transmissive, flooded former coal mine workings as a shallow geothermal resource is a proven technology for heating buildings (Jessop *et al.* 1995; Jardón *et al.* 2013; Verhoeven *et al.* 2014; Athresh *et al.* 2015; Chu *et al.* 2021; Korb 2021; Walls *et al.* 2021; Gasperikova *et al.* 2024; Wang *et al.* 2024). With schemes already operational at larger scales in NE England (Lanchester Wines 2.4 and 3 MW_{th}, Walls *et al.* 2021; Banks *et al.* 2022; Gateshead heat network up to 6 MW_{th}, Coal Authority 2023), a significant opportunity exists in the UK to expand the use of low temperature mine water heating, cooling and thermal storage in the quest to reduce greenhouse gas emissions from fossil fuels and decarbonize heating and cooling of buildings. Such decentralized local energy also increases the resilience and security of energy supply, assuming it can be sustained long term.

Located beneath many highly populated former mining areas of the UK, estimates vary on the theoretical and recoverable size of the resource for heating (Gillespie *et al.* 2013; Todd *et al.* 2019) and cooling/thermal storage (Gluyas *et al.* 2020). Factors that determine the recoverable geothermal resource range from economics, surface demand, land availability, social acceptability (Townsend *et al.* 2020; Starcher *et al.* 2021; Roberts *et al.* 2023) as well as technical geological factors and geo-engineering (Banks *et al.* 2009, 2017; Monaghan *et al.* 2021, 2022; Walls *et al.* 2021). One key aspect is ensuring that the thermal resource, and use of the groundwater that forms the 'working fluid' for the thermal resource, is sustainable over timescales of tens of years of an operational scheme. In basic terms: will the heat run out? In addition, as utilization grows, there is potential for adjacent schemes to interact, positively or negatively. Questions also arise around whether multiple schemes may cause undesirable cumulative environmental impacts.

In the UK currently, no one owns or regulates geothermal heat (Abesser *et al.* 2018, 2023; Abesser and Walker 2022). Mine water geothermal schemes operate under:

(a) groundwater licensing and environmental permitting by environmental regulators;
(b) permit to enter mine workings and Heat Access Agreements from the Coal Authority;
(c) local authority planning procedures;
(d) notice for drilling to the Health and Safety Executive.

Examples of the regulatory and permitting system are given in Starcher *et al.* (2021) and IEA Geothermal (2023*a*). For future increased deployment of the technology, effective decision making on three-dimensional subsurface planning, regulation, licensing and permitting is likely to require an improved technical evidence base. For example, to understand whether heat (or cool) is likely to run out, or the efficiency of thermal storage, the multiple factors controlling temperature and heat transfer in flooded mine systems require better quantification. Critically, this includes the magnitude, extent and timescale of thermal depletion and recharge. In turn, that understanding feeds into values and models of thermal interactions of adjacent geothermal schemes, to complement the better-known pressure/groundwater level responses of adjacent pumped mine water abstractions. Finally, permitting of mine water geothermal schemes rests on subsurface and surface environment interactions (water, gas, chemical, physical), with potential for cumulative impacts from users of groundwater, geothermal and subsurface space.

In this paper, we firstly review multiple technical factors by synthesizing illustrative conceptual models relevant to the processes

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controlling temperature, flow and environmental interactions. By applying these to management approaches for subsurface users of mine water heating, cooling and storage technologies we aim to document:

(a) a greater understanding of the complex geological, hydrogeological and thermal processes in an anthropogenically-altered subsurface;
(b) considerations for the competing demands of multiple subsurface users (e.g. for heat, groundwater, buried utilities and infrastructure, geoenergy storage) in an increasingly crowded subsurface in the UK.

The first section reviews factors controlling temperature and heat transfer in flooded, disused mine workings to examine controls around 'will heat run out? 'and 'how far/how fast?' are induced thermal changes. The second section reviews potential environmental interactions, with literature review around evidence if these have been realized. The interplay of these technical geoscientific factors in management of mine water geothermal schemes is discussed in the third section, focusing on the case of multiple users of the subsurface.

Heat and flow modelling is increasingly used to predict the thermal resource (Renz *et al.* 2009; Rodríguez and Díaz 2009; Peralta Ramos *et al.* 2015; Loredo *et al.* 2016; Mouli-Castillo *et al.* 2024) but a limited number of models are calibrated against operational temperature data (Andrés *et al.* 2017; Driesner 2021). Whilst the mine water heat schemes in Europe, China and USA cited above demonstrate growth and interest in the technology, there is limited quantification of the magnitude, extent and timescale of subsurface thermal transport and heat transfer properties needed to underpin management approaches for mine water geothermal, measured at-scale in real world systems. Two contrasting at-scale infrastructures, the UK Geoenergy Observatory in Glasgow and the Coal Authority Mine Water Heat Living Lab in Gateshead, have extensive instrumentation and sensors that monitor and measure technical hydraulic and thermal parameters to allow novel monitoring programmes. Here we present some early results to develop proof of concept that these sites can quantify at-scale, real world rates and processes by monitoring operations of mine water geothermal-induced changes. Future experimentation and monitoring at these sites will further quantify the evidence base that can be applied to subsurface planning, regulation and licensing of mine water heating, cooling and thermal storage schemes.

Review of geological factors for mine water heating, cooling and thermal storage

A range of processes and factors are at play within flooded, disused mines under both natural conditions and pumping conditions, summarized below. Critical to our understanding of how these influence temperature depletion and recharge are their relative contributions and the rates and magnitudes on which they operate.

Controls on temperature and heat transfer in mine water systems

Factors controlling the supply of heat in coalfield settings have been documented previously (e.g. Banks *et al.* 2004; Gillespie *et al.* 2013) and include:

(a) variability in geothermal sources of heat, e.g. heat derived from radioactive decay (Fig. 1);
(b) contribution of solar heat warming near-surface (surface to *c.* 20 m deep) rocks and groundwater (Fig. 1);
(c) chemical reactions (e.g. sulfide oxidation; Fig. 2);
(d) subsurface urban heat island including ground source heating/cooling/thermal storage boreholes (Fig. 2).

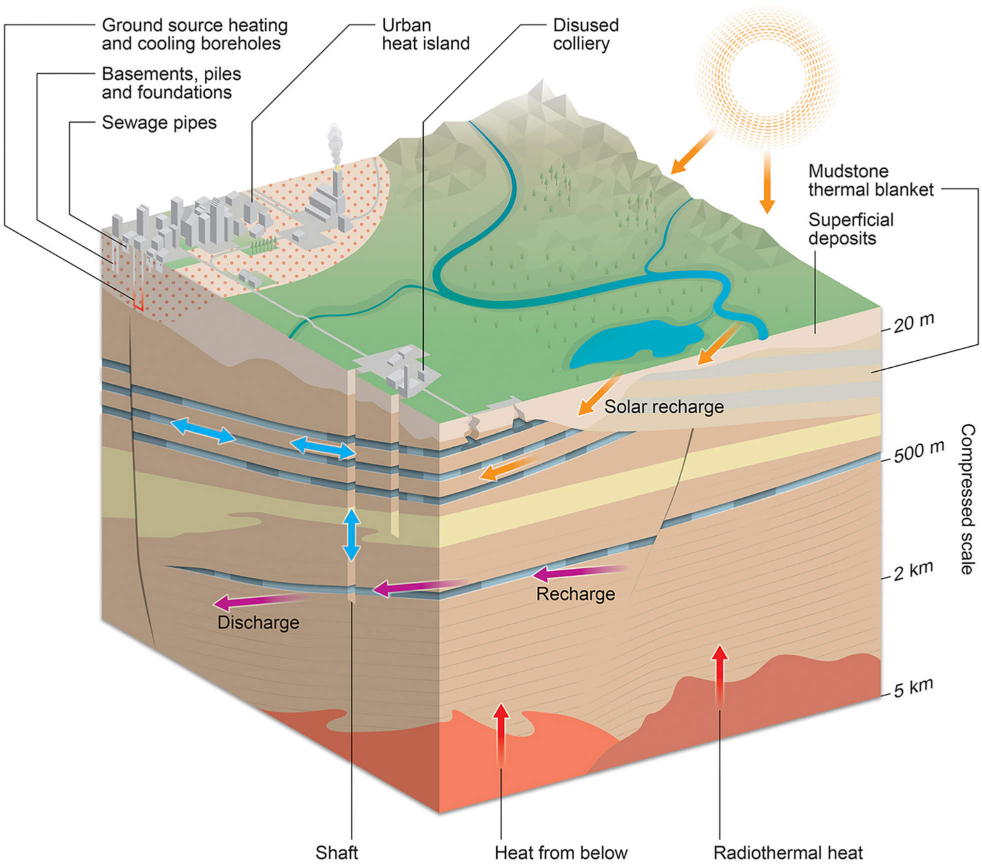

Fig. 1. Block diagram showing predominant heat sources and variations influencing heat transfer in mine water systems. Red arrows represent conductive processes, blue arrows represent groundwater flow in mines and shafts, orange arrows are indicative of heat transfer via solar recharge, purple arrows represent regional groundwater flow, recharge and discharge across the mined rock volume. Source: BGS for © Coal Authority 2022.

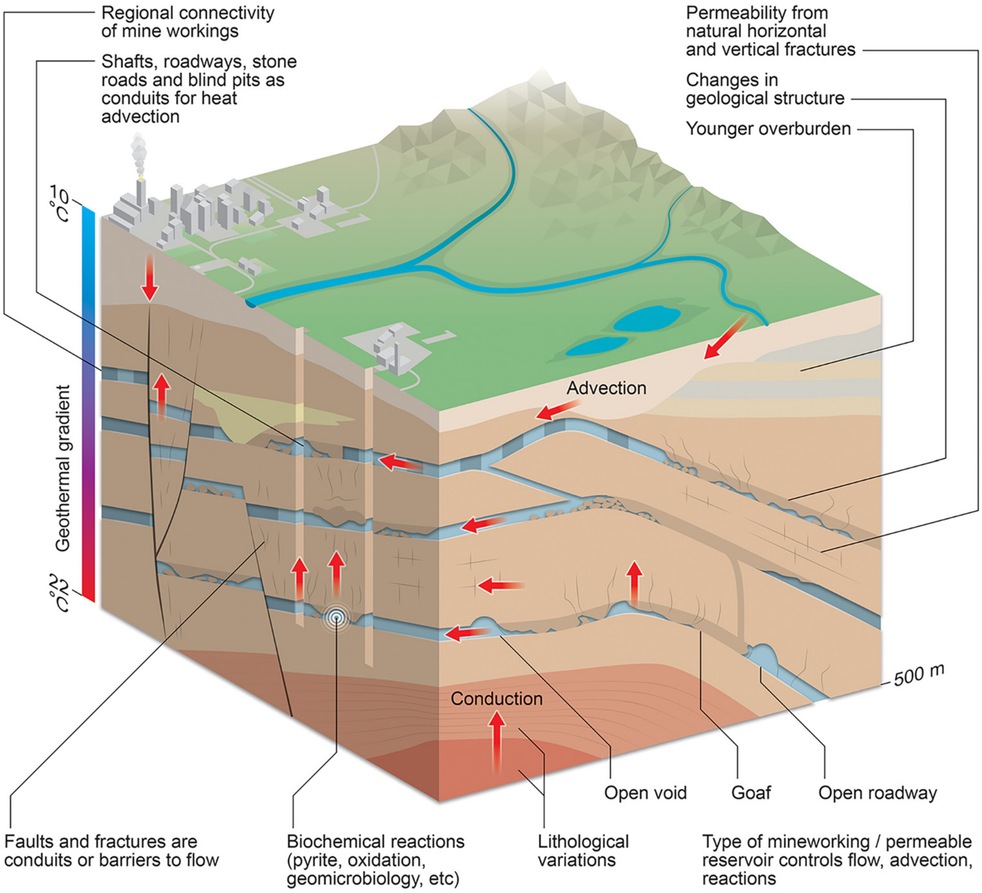

Fig. 2. Geological, hydrogeological, anthropogenic and biogeochemical processes influencing heat transfer processes in flooded coal mine workings, heat transfer indicated by red arrows. The thickness of the mine workings is exaggerated. Source: BGS for © Coal Authority 2022.

Table 1 and Figures 1 and 2 identify key controls and processes on the geothermal gradient (and therefore temperature) and heat transfer, fundamental to managing mine water geothermal schemes and their sustainability.

These variations in supply and transfer of heat manifest themselves in well-documented variations in the UK regional heat flow (e.g. Rollin 1995; Westaway and Younger 2013; Busby and Terrington 2017), geothermal gradients and therefore in estimated subsurface temperatures at various depths (Busby *et al.* 2011). Highest heat flow rates of around 120 mW m^{-2} occur in areas underlain by heat-producing (radiothermal) granites in SW England. Over coalfield areas of the UK, heat flows of around 40–80 mW m^{-2} are most common (Busby *et al.* 2011). A baseline characterization of mine water temperature in Britain's coalfields is given by Farr *et al.* (2020), who document many examples of measured temperature increasing with depth and estimate a median geothermal gradient in equilibrium (not actively pumped) coalfields of 24.1°C/km; mean geothermal gradients in separate coalfields were found to vary from 17.3 to 34.3°C/km.

The relative contributions of the different processes in Table 1 to heat flow and temperature and the timescales over which the processes operate are not well quantified. The dominant process for heat transfer in mines is caused by the bulk movement of water, convection, that can either be free (e.g. because of water density changes) or forced (advective heat transfer e.g. groundwater flow such as driven by a natural hydraulic gradient or caused by pumping) (Wolkersdorfer 2008). Conduction plays a role in the heat transfer in the rock mass and the heat exchange with the mine water and becomes a more important contribution when considering the long-term sustainability of the system (e.g. Loredo *et al.* 2017). Due to the close link between heat and water flow (advection), heat transport in the mines is, to a large part, impacted by the same processes as water, namely the connectivity of the mine system, aquifer properties of the mine workings (open voids, collapsed zones, goaf (rubble formed by collapse of the mine working) and packed wastes (waste rock that miners used to fill mined voids), pillar and stall workings (interconnected 'rooms' separated by intact 'pillars' of coal)) and associated fractured/collapsed zones. However, thermal processes and temperature changes occur on different timescales than the pressure or water-level hydraulic changes transmitted through the mined aquifer system and commonly monitored and managed in the coalfields.

In cities, the mass of anthropogenic material and heat sources – buildings and their foundations, artificial ground, subways and increasingly shallow ground source heating and cooling systems – can both create a thermal blanket and a thermal heat source. Heat transfer from the built infrastructures leads to the subsurface urban heat island effect (SUHI) to depths of 100 m or more (Ferguson and Woodbury 2007; Benz *et al.* 2015; Patton *et al.* 2015; Westaway and Younger 2016; Farr *et al.* 2017; Watson *et al.* 2019; Fig. 1). Studies in non-mining areas have highlighted the role of geology/hydrogeology (e.g. groundwater flow rate in highly permeable layers) on heat transfer in such settings (e.g. Bayer *et al.* 2019; Bidarmaghz *et al.* 2019); a situation likely to be enhanced in mined systems and of importance for heat transport and recovery.

In studies of mining areas of Newcastle/Gateshead and Glasgow, Westaway and Younger (2016) and Watson *et al.* (2019) proposed heat flow perturbations in boreholes to be the result of entrainment and lateral dispersion of heat through flooded mine workings. In the Newcastle/Gateshead example this was within a pumped system. The present thermal state was found to reflect changes since the mining modification took place, retaining no 'memory' of the former thermal state before mining began (Westaway and Younger 2016), highlighting that altered heat-flow processes take place on timescales of less than tens of years. In the Glasgow example, a perturbed, urban temperature profile of Glasgow Observatory borehole GGC01 was attributed to 2.0°C of global warming since the Industrial Revolution and 0.7°C of local UHI

Table 1. Summary of the factors in the control and variation of heat transfer and thus the geothermal gradient and temperature in coalfield settings, referenced to the relevant image

Controls on the geothermal gradient	Conductive heat transfer (Fig. 1)	Advective (convective) heat transfer (transport by water or other fluids; Fig. 1)	Surface topography	Climatic and anthropogenic temperature changes
Factors controlling variation in heat transfer under natural conditions (not actively pumped) coalfield systems	Lithology and stratigraphic geometry (successions, dips etc). In inclined strata, heat refraction, i.e. conductive heat transfer, deviates from vertical	Groundwater flow: recharge and discharge (Figs 1 & 2). Lateral flow in mine workings; upwards/downwards/or stratified in shafts.	Control on surface temperature and on recharge/ discharge pathways	Geologically recent climate change (glaciation)
		Aquifer/reservoir properties (transmissivity, porosity etc.) dependent on type of mining and post-closure history (Fig. 2)		Current-day climate change
	Lithology controlled rock properties (thermal conductivity, specific heat capacity). Low conductivity rocks 'thermal blanket' (Malolepszy 2003)	Geometry and connectivity of mine system including connecting shafts (Fig. 2). Faults and fractures: sealing or non-sealing (open). Natural and mining-induced (Fig. 2)		Near-surface temperature changes from the SUHI: type of buildings, basement, wastewater, soil use, asphalted/paved, sewage pipes, tunnels, groundwater and ground source heat boreholes, waste heat, solar heat production
Factors controlling variation in heat transfer in actively pumped coalfields and pumped/geothermal systems	As above	As above plus: Flow rate and duration of pumping (continuous, some hours per day, seasonal). Longevity of pumping operations (days–tens of years). Water level/recovery rate controlled by pumping. Pumping in shafts (dependent on mine geometry/ hydrogeology, pumping depth (Farr *et al.* 2020; Receveur *et al.* 2021). Geothermal systems: Open loop with return to mine working v. discharge of mine water. Abstraction–re-injection setup (e.g. distance and across mine working connectivity – flow path length) Geothermal systems: temperature (thermal) load applied (ΔT)	As above	As above

Information sources listed for specific items and synthesized for widely documented phenomena including from Banks *et al.* (2004) and Gillespie *et al.* (2013). SUHI, subsurface urban heat island.

development. The shallow subsurface was warmer than it would have been before the Industrial Revolution to around *c.* 90 m, and colder below that depth, interpreted to be due to the high permeability effect of mine workings (Watson and Westaway 2020).

Heat-flow modelling is a fundamental step to predict and manage the geothermal resource, providing the quantitative information of temperatures, thermal outputs etc. over timescales of hours to years that are necessary for assessment and planning. Different approaches provide complementary insights; analytical approaches solve the exact mathematical equations and are appropriate for simplified processes and scenarios; numerical models provide outputs over more complex problems and geometries, such as those characteristic of flooded mines (Loredo *et al.* 2016, 2017). In contrast to modelling in natural porous media aquifers with well-established workflows, an important limitation of numerical modelling in flooded mine workings is the lack of generalized modelling strategies for simulation of groundwater flow and heat transport in interconnected voids (pipe flow) and fractured rock, as well as porous media. Modelling approaches in mined systems vary dependent on the question being asked and, as with all models, are 'an assemblage of simplifying assumptions about a complex, real system, which achieves a valid representation of that system' (Younger and Adams 1999, p. 39). In mine models, limitations include uncertainty in the model conceptualization and regional hydrogeological boundaries, high computational requirements of solving a multiphysics problem, detailed geometrical models, uncertainty in the extent and parameterization of hydraulic and thermal properties (roadways, open voids, backfilled, goaf and collapsed zones).

Summarizing, advection processes are dominant in mined coalfields, with pumping playing an important role in the thermal profiles of coalfields (e.g. Westaway and Younger 2016). An improved evidence base on the key controls on and values of rate and magnitude of heat transfer processes are needed; early results from at-scale instrumented sites are provided below.

Integrated heating, cooling and thermal storage

With interest growing in low temperature district heating and cooling networks (e.g. 5th Generation District Heating and Cooling that uses direct exchange of warm and cold flows and thermal storage to balance thermal demand) and in interseasonal and electrical grid intermittency balancing using underground thermal storage, the role of integrated heating, cooling and thermal storage in mine water energy is increasingly important. Clearly, integrated heating/cooling/storage schemes are grounded in subsurface heat transfer and exchange processes that affect subsurface temperatures. They are likely to increase the resilience of mine water geothermal (and geothermal subsurface use in general) by mitigating against heat depletion by over-abstraction of heat or by multiple adjacent users. Excellent understanding of local thermogeology and processes will be needed for sustainable management (e.g. to avoid thermal dispersion from groundwater flow; or interferences between warm and cold cells), along with improved understanding of cumulative heat-flow cycling and heat recovery efficiency. Provision of heating *and* cooling may present an opportunity to thermally balance these schemes, possibly improving their long-term sustainability.

Significant thermal storage potential in UK flooded mines has been estimated by Gluyas *et al.* (2020, *c.* 16 TWh, ΔT 5°C scenario). For thermal storage in mine workings, the idealized geological factors influencing temperature are different from those for heat abstraction with the need to keep stored heat in place (e.g. lithology (Silva *et al.* 2022), faults and fractures, geometry; limited recharge/discharge). A number of active research projects are investigating this further at demonstration sites. High temperature mine thermal energy storage ('HT-MTES', ΔT 50°C) is being tested in Bochum, Germany, using heat transferred from solar collectors to a mine working at 74 m depth (Heatstore 2022). Pilot projects are also in progress in the UK to examine 'geobattery' thermal storage and transport in mine workings (Fraser-Harris *et al.* 2022) and application to waste heat from a computer data centre (Galleries to Calories project University of Edinburgh 2024), investigating thermal storage in mine shafts from curtailed wind energy (STEaM project, Geothermica 2024) and in Cornwall using surplus heat from the United Downs geothermal scheme for high temperature storage in nearby mines (PUSH-IT 2024).

Review of potential environmental interactions

In addition to management of depletion or replenishment of the thermal resource, mine water heating, cooling and thermal storage schemes have potential to induce change in, and interact with, the wider subsurface and surface environment (Fig. 3, Tables 2 & 3). Changes could be beneficial, for example improved groundwater management and monitoring, use of the SUHI, as well as reduction in CO_2 emissions from heating. Or conversely, changes may adversely affect the status quo and require mitigation (Table 2). Typically, these factors are identified during the planning and permitting process, and measures are specified for their monitoring and/or mitigation. For example, regulatory, permitting and guidance processes for drilling, groundwater abstraction and recharge in coalfields may include obligations for the monitoring of groundwater, surface water levels and geochemistry, gases in water, soils and near surface, ground motion (Tables 2 & 3), as well as a requirement for considering the cumulative impacts of multiple abstractions/disposals. The potential impacts depend on the type of geothermal scheme (open loop with re-injection to mine workings or shaft; open loop with discharge to a mine water treatment scheme; closed loop), the depth and scale of operation and the local geology/geometry/hydrogeology (Banks 2012; Preene and

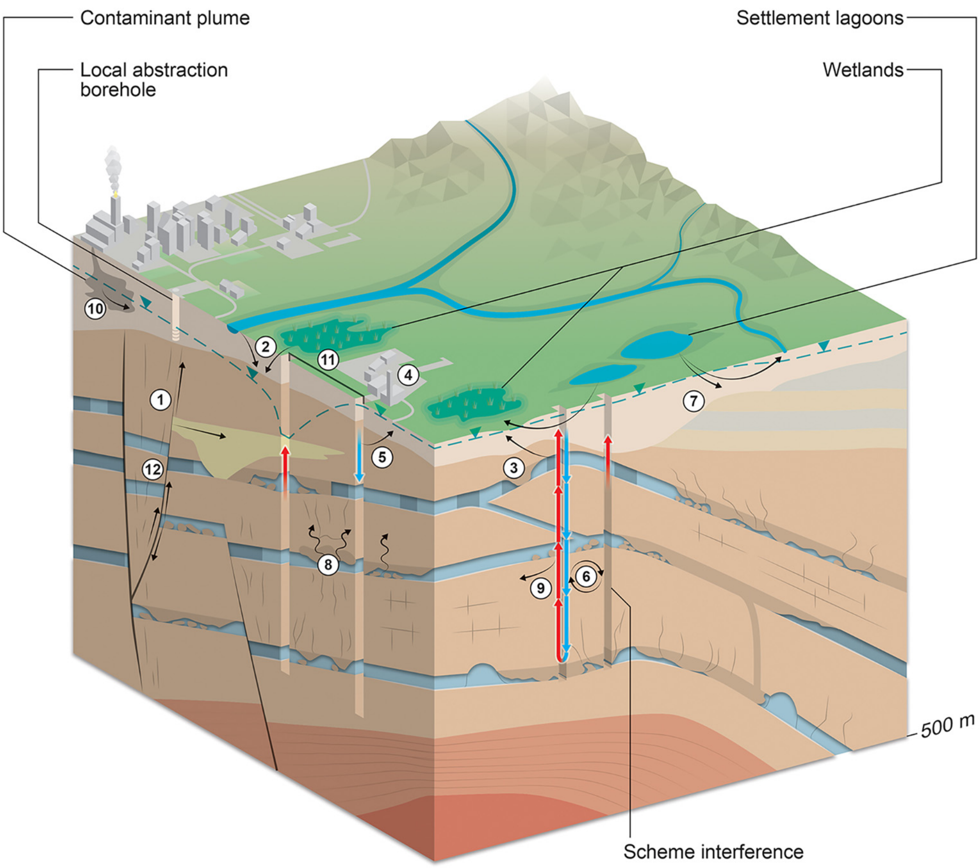

Fig. 3. Potential environmental interactions and impacts of mine water energy schemes on groundwater, surface water, geomechanics and geochemistry: 1, fault reactivation leading to fluid movement; 2, reduction in groundwater levels; 3, subsidence; 4, increases in groundwater levels; 5, leaks from casing; 6, mine water scheme interference; 7, changes to groundwater–surface water flows; 8, risk of biofilm clogging/biogeochemical reactions; 9, leakage of heat transfer fluid (closed loop system); 10, mobilization of contaminants from industrial sites; 11, cumulative land use impacts; 12, fault creep or slip. This image does not cover drilling or operational surface engineering. Source: BGS for © Coal Authority 2022.

Table 2. Summary of potential environmental interactions of mine water energy schemes on groundwater, surface water, geomechanics and geochemistry (numbers in brackets are on Fig. 3), monitoring methods, examples of current UK regulatory, permitting and guidance

Potential environmental interactions grouped thematically by monitoring method/regulatory framework	Monitoring method	Methods for data gathering	Examples of UK regulation/standards/guidelines
Reduction/drawdown in groundwater levels (2) Increases in groundwater levels (4) Local abstractions – quantity	Groundwater – temperature/flow/level	Borehole testing (pumping tests etc). Borehole monitoring, e.g. data loggers, manual measurement, fibre optics, geophysical monitoring, tracer testing	EA/SEPA/NRW/NIEA regulatory frameworks for groundwater abstraction, disposal and geothermal guidance. British Standards
Local abstractions – quality Leaks from casing (5) Leakage of heat transfer fluid (closed loop) (9) Risk of biofilm clogging/biogeochemical reactions (8) Mobilization of contaminants from industrial sites (10)	Groundwater – chemistry	Hydrogeological field parameters, sample collection and laboratory analysis. Standard suites and contaminants of concern	British Standards: EA Best Available Techniques: SEPA: Contaminated land CL:AIRE guidance: EA Source–pathway–receptor assessment
Changes in groundwater flows to surface water bodies and dependent ecosystems (Younger *et al.* 2002) (7), or to groundwater flooding	Surface and ground water – chemistry	Hydrogeological field parameters, sample collection and laboratory analysis. Standard suites and contaminants of concern	Environmental quality standards: SEPA (2014, 2019); UKTAG (2013)
Mobilization of contaminants from industrial sites (10)	Soil chemistry	Sample collection and laboratory analysis. Standard suites and contaminants of concern	CL:AIRE guidance; British Standards
Risk of biofilm clogging/biogeochemical reactions (8)	Geomicrobiology	Geomicrobiology characterization (DNA, RNA)	n/a
Subsidence (3) Fault reactivation leading to fluid movement (1)	Ground motion	InSAR analysis. On the ground repeat surveys. Inclinometers. Hydrogeological monitoring	n/a
Fault reactivation (12)	Aseismic movement, ground motion or induced seismicity	Seismic and microseismic monitoring, fibre-optic acoustic monitoring (DAS)	Earthquake magnitude (M_L)
Gas (CO_2, CH_4, H_2S)	Gas migration	Soil (ground) gas monitoring, near-surface gas monitoring, gas monitoring at boreholes	Coal Authority/HSE guideline on drilling (2019)
Cumulative land use impacts (11)	Surface – ecosystems	Ecological surveys – standard practice in environmental consultancy	British Standards
Mine water scheme interference (6). Changes in performance (negatively or positively)	Groundwater – temperature/level. Heat pump efficiency	Hydrogeological logger and other temperature measurement (DTS, thermistor strings). Heat pump coefficient of performance (COP)	Groundwater and coal mine permitting and licensing
Thermal exchange with basements, foundations, sewers, tunnels, other ground source heat boreholes (10) (negatively or positively)	Temperature and flow monitoring	Hydrogeological logger and other temperature measurement (DTS, thermistor strings and temperature in the built infrastructure)	n/a

Younger 2014; Zhu *et al.* 2017; VoGERA 2019; Crowdthermal 2020; Environment Agency 2021).

In understanding potential environmental impacts, an appropriately designed monitoring system is an important tool to evidence that there has been no impact on the environment, or to provide an early warning system if impacts are seen (Fig. 3, Table 2).

Hydrogeological system

In coalfields, the baseline hydrogeology of Coal Measures strata is complex due to the multi-layered nature that favours development of multi-aquifer systems (e.g. Ó Dochartaigh *et al.* 2015; Banks *et al.* 2022), modification of hydrogeochemistry by mining activities (Younger 2001; Younger *et al.* 2002; Loredo *et al.* 2017) and post-mining groundwater rebound (Younger and Adams 1999; Burke and Younger 2000). A robust geological and hydrogeological conceptual understanding of the area and incorporation of hydrogeological expertise into design and development of mine water schemes is essential to avoid well interference and unrealistic expectations of yield (Banks *et al.* 2022). Processes to be considered in engineering design and environmental monitoring of the hydrogeological system include:

(a) open-loop mine water heat schemes with abstraction and re-injection of mine water may modify groundwater flow

Table 3. High level summary of processes, potential causes and risks related to geomechanical/rock property changes associated with mine water geothermal and summary of evidence of occurrence, compared with the evidence from the original mining activities

Process	Potential causes – mine water geothermal	Risk – mine water geothermal	Evidence it occurs during mine water geothermal operations	Evidence the process occurred during mining or during post-abandonment groundwater rebound
Local collapse within flooded, disused mine workings	Turbulent flow causes pillar spalling/goaf/stowage erosion leading to lack of roof support (Younger 2014) Flow or pressure-induced local stress changes (e.g. water level drawdown to beneath roof of mine working removing buoyant support, Younger 2014) Thermal changes induce pressure changes (e.g. models in Todd *et al.* 2019, 2024), in turn inducing pillar collapse or upward ground movements. Natural seismicity nearby	Limited upwards void migration, possibly leading to • damage to borehole • change in hydrogeological, thermal properties at the borehole or connectivity of the mine water reservoir. • increased fractures underlying or overlying the mine working	None found in UK literature review	Evidenced in field and opencast exposures, borehole data
Large collapse within flooded, disused mine workings (e.g. multiple pillars or seams) leading to crown hole formation	Induced locally by turbulent flow, pressure/stress changes or thermal changes (as above) – leading to chain effect of multiple collapses in pillar and stall workings or stacked workings	More significant upward migration leading to surface ground motion and subsidence	None found in UK literature review	Examples of surface collapses from NCB (1975), Healy and Head (1984), Mason *et al.* (2019)
Fault reactivation	Pressure increases during re-injection result in aseismic fault slip on pre-existing natural faults (Noting mine workings are shallower than other geoenergy technologies; re-injection pressure is low)	Possibility for differential subsidence across pre-existing faults	None found in UK literature review	Donnelly (2006), Donnelly *et al.* (2008)
Felt seismic event caused by geothermal activities	Pressure increases during re-injection result in sudden fault slip/seismicity on pre-existing natural faults in stress states/ orientations close to failure (noting mine workings are shallower than other geoenergy technologies; re-injection pressure is low)	Felt seismicity and surface damage	None found in UK literature review	Baptie *et al.* (2016) – seismicity from mine collapses during mining
Regional ground motion	Regional changes in water level due to changes in pumping regime	Uplift or subsidence	None found in UK literature review	e.g. Bateson *et al.* (2015), Gee *et al.* (2017); Sowter *et al.* (2017) after pumps have been switched off across whole coalfields

regimes locally, reduce or increase groundwater levels in the surrounding aquifer, or alter fluid movement pathways around faults. The magnitude and extent will be dependent on aquifer properties and pumping rates;

(b) drilling of boreholes may create a hydraulic connection between otherwise isolated aquifers, creating potential contamination pathways or mixing of waters of different hydrogeochemistry (Banks 2012);

(c) potential for leaks from the casing due to poor construction or from closed-loop systems carrier fluid (Zhu *et al.* 2017) could cause environmental impacts if leaked into mine water or overlying aquifers used for water supply;

(d) changes in temperature affect solubility of minerals and gases in water and may increase rates of chemical reactions, or biogeochemical reactions where increased microbial activity can lead to biofouling (clogging of the wells or pumps, Osvald *et al.* 2017).

Monitoring of groundwater level and temperature, as well as surface and groundwater quality may be required for permitting and licensing (Table 2).

Geomechanics and ground motion

Mining has created significant changes in the geomechanics (strength, pressure, stress state) and properties (porosity, permeability, hydraulic conductivity etc.) of the rock mass. Active mining in the UK commonly caused subsidence (e.g. NCB 1975; Healy and

Head 1984; Mason *et al.* 2019) and induced seismicity events due to collapses (e.g. Al-Saigh and Kusznir 1987; Baptie *et al.* 2016; including planned collapses in longwall mining; most less than earthquake magnitude 2.6 M_L; Table 3). During the years following mine abandonment and flooding, localized subsidence of older, shallow workings (e.g. Bell and De Bruyn 1999), regional changes in ground deformation (commonly uplift associated with mine water rebound: e.g. Bateson *et al.* 2015; Gee *et al.* 2017) and accompanying aseismic slip/differential subsidence on natural faults (Donnelly *et al.* 2008) have also been observed (Table 3). These observed mining-related impacts logically lead to questions on whether mine water geothermal will cause subsidence or seismicity (e.g. Environment Agency 2021).

The size/scale of the pumping, temperature, water level and flow changes involved in mine water geothermal (e.g. pumping rates 20–40 $l\ s^{-1}$, 27 m maximum drawdown at two Lanchester Wines schemes, Gateshead in Banks *et al.* 2022; up to 140 $l\ s^{-1}$ at Gateshead Heat Network, IEA Geothermal 2023*b*) are orders of magnitude less than those induced by the historical mining operation itself (e.g. Harrison *et al.* 1989, table 1, multiple working mines pumping at hundreds of litres per second to maintain water levels at −107 to −570 m below Ordnance Datum) or by rebound of groundwater after cessation of pumping at coalfield scale (Younger and Adams 1999; Gee *et al.* 2017).

Whilst there is extensive knowledge of mining-related geomechanics and property changes, limited numbers of studies relate to mine water geothermal operations specifically. Banks (2012) and Younger (2014) summarize that collapse/subsidence are likely to affect only the shallowest and least stable workings. Probability of fault slip on certain fault orientations during mine water geothermal activities based on modelled stress field, fluid pressures and rock properties for the South Wales Coalfield noted significant uncertainty in rock property input parameters (Healy and Hicks 2022). Coupled thermal–hydraulic–mechanical modelling of pillar and stall workings by Todd *et al.* (2019, 2024) indicated that cyclical injection and abstraction of heat impacts the modelled mechanical stability of the system. However, modelled risk impacts from controllable factors (temperature, amount of water re-injected) were of greater importance than geological and mine geometry.

Mitigations for mine water geothermal operations are therefore likely to include not utilizing the shallowest mine workings and limiting drawdown of groundwater levels. Reducing pressure increases by balancing the flow rate and volume or mine water abstracted with that re-injected, commonly into another part of the same mine water body, is considered in some regulatory regimes (e.g. Scottish Environment Protection Agency GBR17, SEPA 2022). In deep geoenergy technologies, induced seismicity is most often associated with high-pressure re-injection of waste water and the resulting increase in pore fluid pressure on already critically stressed faults on certain orientations (e.g. Deichmann and Giardini 2009). Mine water geothermal differs from these geological situations in several regards: (i) re-injection pressures are low as the mine water system is an extensive, highly permeable reservoir, commonly with connections to atmosphere through shafts and other mine entries; (ii) mine water re-injection levels are likely to be relatively shallow, pressures at these depths are far lower than re-injection at a few kilometres depth; and (iii) the impacts of mining activities are likely to have already altered the shallow stress state, such as faults with stress build up.

Destabilization of disused mine workings via poorly designed boreholes resulting in removal of supporting backfill material ('goaf'), or erosion of open roadways and pillars may also be considered a risk for mine water geothermal activities. However, in considering crown-hole formation (surface collapse) from erosion or removal of buoyant support due to pumping, Younger (2014, p. 15) states that

> no examples of such induced crown-holes are reported from the numerous Coal Authority pumping operations in the UK. The risk can thus probably be dismissed for all but the shallowest of mine workings in the most unstable strata.

The converse process of sedimentation leading to deterioration of the mine water reservoir properties after mine abandonment has also been documented (Andrews *et al.* 2020).

Thus, whilst pressure, flow and thermal changes induced by mine water geothermal schemes could theoretically affect a range of geomechanical processes that may result in ground motion (Table 3), literature review provides no examples of impacts being observed in the UK, and a number of mitigations can be applied.

Gas

During deep coal mining in the UK, gas and gas migration (CO_2, CH_4, H_2S) formed a significant hazard in some areas and is also a consideration during mine water recovery with rising groundwater levels (Burrell and Whitworth 2000). However, since mine water energy schemes are generally installed in flooded mines with recovered water levels, there is usually little or no space for free gas to accumulate. Gas and fugitive emissions have not thus far been documented as a significant environmental challenge for mine water geothermal and can easily be monitored during development and operation of mine heat schemes. Gas monitoring and mitigation measures are part of best practice when drilling into disused mines and form a requirement of The Coal Authority Permit to Enter (Coal Authority *et al.* 2019; Dennehy *et al.* 2019). Evaluation of data on dissolved and headspace gas for operational schemes is important to assess potential risks of explosion or asphyxiation.

Management for multiple geothermal users

Multiple mine water geothermal users of the same subsurface

Subsurface management approaches for multiple users of the same 3D volume have been examined in a number of settings. In urban areas, using case study examples from the Netherlands, Griffioen *et al.* (2014) recommended that: management of the resource should be driven by the principle of scarcity, baseline monitoring should be implemented for high risk subsurface activities, the precautionary principle should be used for unknown features; and heterogeneity, and sustainability, responsibility and liability for damage should be set out in legislation. Applying these to UK mine water geothermal, the potential scarcity of the thermal resource if tapped by multiple users and its interaction with buildings, sewers, tunnels is not well understood, thus it is essential that baseline monitoring takes place. Regulation covers groundwater management, sustainability, responsibility and liability more broadly. Specifically for shallow urban geothermal technologies, MUSE (2022) provided case studies highlighting the value of monitoring data in management regimes, Abesser *et al.* (2021) provide examples of shallow geothermal system interference affecting the thermal and hydraulic regime and ground source heat pump efficiency and Duijff *et al.* (2023) examine the effect of well placement, interaction effects and recovery efficiency.

Approaches considered by other subsurface technologies to multiple users of the same volume can provide insights. These include screening methods for groundwater vulnerability based on multi-factor geological and hydrogeological parameters (Loveless *et al.* 2019) and 3D buffer zones around disused mine workings (Monaghan 2017). A regional, basin-scale management approach with monitoring of key parameters, along with merging of field- (site) scale models and datasets has been suggested in the case of multiple users of the same CO_2 storage reservoir (Akhurst *et al.* 2015). For that technology, to balance operator and regulator requirements in a 'multi-store' reservoir, the workflow firstly sought to establish if interaction was negligible, avoidable or acceptable. It also considered that multiple users could have beneficial as well as adverse effects and how the CO_2 injected at one site be distinguished from that injected at another (Akhurst *et al.* 2015). Transferring that to mine water geothermal, in a system with multiple operators, temperature and pressure/water level are likely to be key parameters, though an improved evidence base is needed to understand rates and magnitudes of processes at regional and site scale. Also, integrating heating, cooling and storage applications (sections above) may turn potentially adverse effects into benefits.

Mine water blocks

Collieries in the UK commonly contained multiple levels of coal mine workings linked by shafts and roadways. They can form large connected systems. In addition, adjacent collieries may be physically connected by mine workings or roadways. There is also the potential for hydrogeological connectivity between disparate mine workings through natural aquifers (e.g. sandstones) and permeable faults (Ó Dochartaigh *et al.* 2015, fig. 11).

The method of management of mine water hydrogeological systems used by the Coal Authority includes defining 'mine water blocks' and 2D hydrogeological conceptual models (Coal Authority 2018). Within each block is a set of flooded mine workings, which are sufficiently well interconnected that within current water management strategies, they exhibit a continuous hydraulic response across their area. Conversely, different mine water blocks are generally hydraulically isolated from each other or have connections that do not allow equalization of water level gradients between them. Mine water blocks are based on current mine water management strategies for environmental protection, some of them are based on British Coal/NCB management boundaries and require assessment and development to improve understanding. Some are based on assessment of mining information, water level monitoring data and, in some areas, in-seam connections and vertical connections (Coal Authority 2018). The nature of the mining, mining connections and surrounding geology results in mine systems and blocks that can be dynamic. Regular assessments of mine water data and mining information are needed to confirm mine water block understanding and correct management strategies are being used (Wyatt *et al.* 2023).

Management strategies, permitting and mine water heat access agreements to mine workings for heat/cool/storage by the Coal Authority utilize the understanding of mine water blocks and 2D hydrogeological conceptual models where available. Logically, mine water geothermal schemes in different mine water blocks are unlikely to interact on operational timescales of mine water energy schemes. Applying a precautionary principle of one mine water scheme per block to prevent scheme interactions could be a logical initial step, paralleling the subsurface management approach in Griffioen *et al.* (2014). Mine water blocks can often be tens of kilometres wide and with multiple different seams being mined. In a mine water block, there could be multiple opportunities for operational geothermal schemes. Where the mine workings are being utilized for heating, cooling or storage, there is limited understanding of extent, magnitude or duration of thermal changes within and between the mine workings. Hence, gathering further information and technical evidence via at-scale monitoring is the logical next step (sections above and below), to avoid unnecessarily limiting utilization of the thermal resource and unwanted thermal interactions. Such an evidence base from monitoring will facilitate evaluation of whether interactions are negligible, avoidable, acceptable or beneficial. It will further improve understanding of the role of integrated heating/cooling/storage schemes and heat networks in increasing resilience, and inform 3D subsurface planning of the resource.

Review of mine water heat schemes globally provides some insights. The heating and cooling network at Heerlen, Netherlands uses mine water geothermal as a baseload and incorporates heating and cooling loads at different depth levels and locations in the same colliery (Verhoeven *et al.* 2014). Initially conceived as a heating scheme, initial operational data and predictive modelling indicated homogenization of temperatures after a period of about 2 years (Verhoeven *et al.* 2014). Though management is via one operator and one multi-level mine, so simpler than with multiple operators and multiple former collieries, Heerlen currently uses 5 bi-directional wells for commercial, housing and educational users and shows sustainable management of adjacent heating and cooling loads, at scale (IEA Geothermal 2023*c*). Another example is the flow and heat modelling undertaken during planning for multiple heat 'feed-in' and 'feed-out' systems at the Dannenbaum mine water scheme, Bochum, Germany (Bussman *et al.* 2019), also within one operator and mine.

Observations from hydrogeological monitoring of UK coalfields highlight the importance of depth, laterally and vertically separated aquifer systems in 3D subsurface planning for thermal utilization. Younger (2016) provides evidence from the Selby area that deep coal mines were developed in complete hydraulic isolation from the near-surface hydrogeological environment (older, shallow mines and Permo-Triassic aquifer), despite significant stratal disruption from deep mining. In addition, extensive monitoring of the Lanchester Wines mine water heat scheme at Gateshead describes three vertically discontinuous aquifer systems at the site (Banks *et al.* 2022). Some water-level changes (pressure responses) are observed within and across aquifers between the two sites (700 m apart) and the Gateshead mine water scheme (1.9 km away). However, at the time of publication, Banks *et al.* (2022) had not found convincing evidence of thermal breakthrough from injection of cooled water into the High Main Seam at Abbotsford Road affecting the abstraction borehole at Nest Road 700 m away, and monitoring was continuing. Based on the most recent and updated assessment of the mine water blocks, these multiple mine water heat schemes lie within the 'Walker' mine water block at Gateshead, UK, which serves as a key area for understanding the challenges of multiple and resilient subsurface use and is also the location of the Coal Authority Mine Water Heat Living Lab observation boreholes described below.

Discussion: management approaches and knowledge gaps

As interest in mine water geothermal schemes increases, beneficial approaches based on system understanding that permit wider use of the resource become desirable. Smaller units for geothermal permitting could take approaches of 3D heat blocks, heat protection zones providing a thermal catchment around geothermal schemes (similar to a source protection zone for groundwater) or areas interfacing with surface 'heat zoning' plans that may incorporate heat/cool/storage. Controlling factors to thermal sustainability include the scale of geothermal scheme being proposed (pumping flow rate and ΔT thermal load) and its longevity, as well as geospatial connectivity and extent of responses (Table 1). To define management approaches, the sections above highlight knowledge and evidence gaps in:

(a) thermal responses, rates of heat transfer, replenishment and sustainability that control temperatures on timescales of operational mine water geothermal schemes, under different structural and recharge–discharge regimes;

(b) updated 2D and 3D hydrogeological conceptual model types under pumping at site-specific to mine water block scale, including in-seam and vertical connectivity;
(c) monitoring of thermal and other impacts from varying magnitudes of mine water heat/cool/storage schemes, and between multiple schemes;
(d) cumulative effects from multiple users from long-term cycling heat/cool.

Whilst all sites will be different, the next steps for the sustainable planning of mine water geothermal schemes include investigations to understand the most critical, sensitive and transferable factors for monitoring and management.

Early insights: evidence base from at-scale sites

As discussed above, quantifying the rate and magnitude of heat transfer and replenishment processes, needed for management of mine water geothermal resources and environmental changes, requires measurement of parameters such as groundwater level, flow, groundwater and rock temperature (Table 2). This section summarizes such instrumentation and sensing capabilities installed at the UK Geoenergy Observatory, Glasgow and the Mine Water Heat Living Lab, Gateshead, as well as demonstrating early monitoring results of baseline temperatures and temperature changes induced by geothermal operations.

UK Geoenergy Observatory, Glasgow

Infrastructure and monitoring capabilities

From 2017–22, the UK Government, through the Natural Environment Research Council funded capital investment of the UK Geoenergy Observatory in Glasgow. Construction and subsequent operations are through the British Geological Survey (BGS). The infrastructure includes four mine water boreholes in a sealed open loop currently configured as two abstraction and two injection boreholes. The boreholes are spaced between 10 and 190 m apart, two are screened at the Glasgow Upper mine working 45–50 m below ground and two at the Glasgow Main mine working approximately 85 m below ground (details in Monaghan *et al.* 2021). Abstraction boreholes are equipped with variable speed submersible well pumps optimized for flow rates between 3 and 12 l s^{-1}. The mine water pipe is connected to a heat centre with three types of heat exchanger, a *c.* 200 kW output heat pump/chiller for active heating or cooling of mine water, as well as a sensor logging system (Fig. 5a). Equivalent to the demand of a municipal building or tens of houses, experiments can be run in different doublet configurations to investigate heat and flow processes, in conjunction with a range of environmental monitoring.

The six boreholes that penetrate fully flooded, disused mine workings have fibre-optic cables used for distributed temperature sensing, and downhole electrodes to measure subsurface electrical resistivity, installed on the outside of the borehole casing. The fibre-optic cables allow detection of small changes (±0.01°C) in temperature at high spatial resolution (e.g. every 0.25 m along the fibre). The electrodes enable in-hole and cross-hole tomography (ERT) for tracking subsurface changes in 4D (time as fourth dimension).

There are five additional environmental monitoring boreholes screened across either bedrock or superficial deposits. In common with five of the boreholes penetrating mine workings, these are equipped with downhole hydrogeological loggers that measure temperature, pressure and specific electrical conductivity. The early results presented below utilize hydrogeological logger temperature data from the baseline and during a thermal storage commissioning test, as well as measurements from the distributed temperature sensing to examine the magnitude and rates of thermal changes.

The subsurface monitoring is complemented by gas monitoring (soil gas probes, scanning lasers, surveys), a weather station, surface and groundwater hydrogeochemistry surveys; seismic and ground motion (InSAR) monitoring and a 199 m cased borehole containing a string of seismometers (Monaghan *et al.* 2022, 2023). Construction, test pumping and environmental monitoring data are openly available via www.ukgeos.ac.uk.

Measured baseline data

Over three years of groundwater monitoring data from downhole hydrogeological pressure, temperature and specific electrical conductivity loggers reveal baseline variations in these parameters before geothermal testing began. Pressure readings providing calculated water levels show both annual and daily solar and lunar tidal signals in mine water boreholes screened at *c.* 50 m and *c.* 85 m below ground level (Monaghan and Spence 2023). In contrast, the measured groundwater temperatures at the loggers positioned between 10 and 24 m downhole in mine water, bedrock and superficial deposits boreholes are relatively constant, between 11.1 and 11.8°C (Figs 4 & 5a) and of smaller magnitude than geothermal loads to be applied (ΔT 2–6°C). Exceptions include an expected cooling trend after test pumping in February 2020; a warming–cooling curve in GGA01 between July and December 2020, peaking at 12.7°C; and an unexplained cooling trend in GG07 and GGA08 to 10.9°C between December 2020 and March 2021, which ended when the depth of loggers was changed

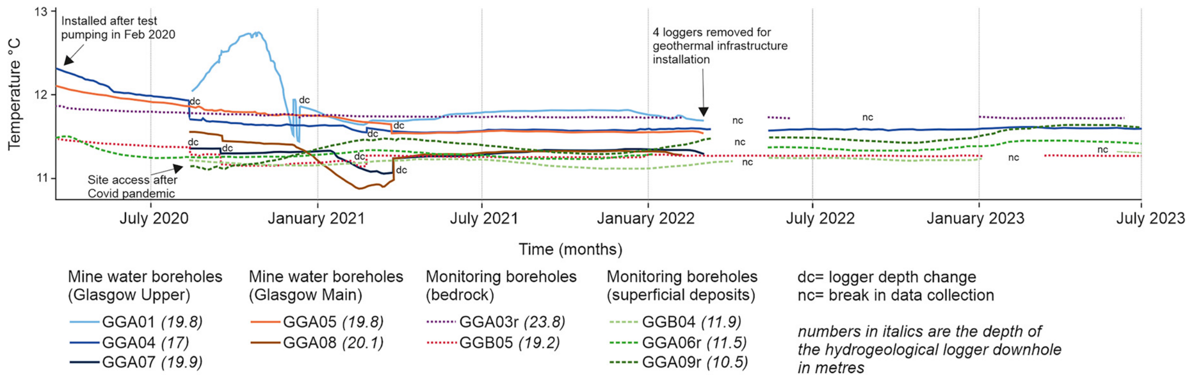

Fig. 4. Plot of the temperatures recorded in downhole loggers at the UK Geoenergy Observatory in Glasgow over a 3-plus year period. Spikes corresponding to loggers being removed from boreholes for download have been removed from this plot. Note the loggers are above the level of the screened interval (e.g. mine working) except those in the superficial deposits. Source: BGS © UKRI. Contains NERC materials © NERC 2024.

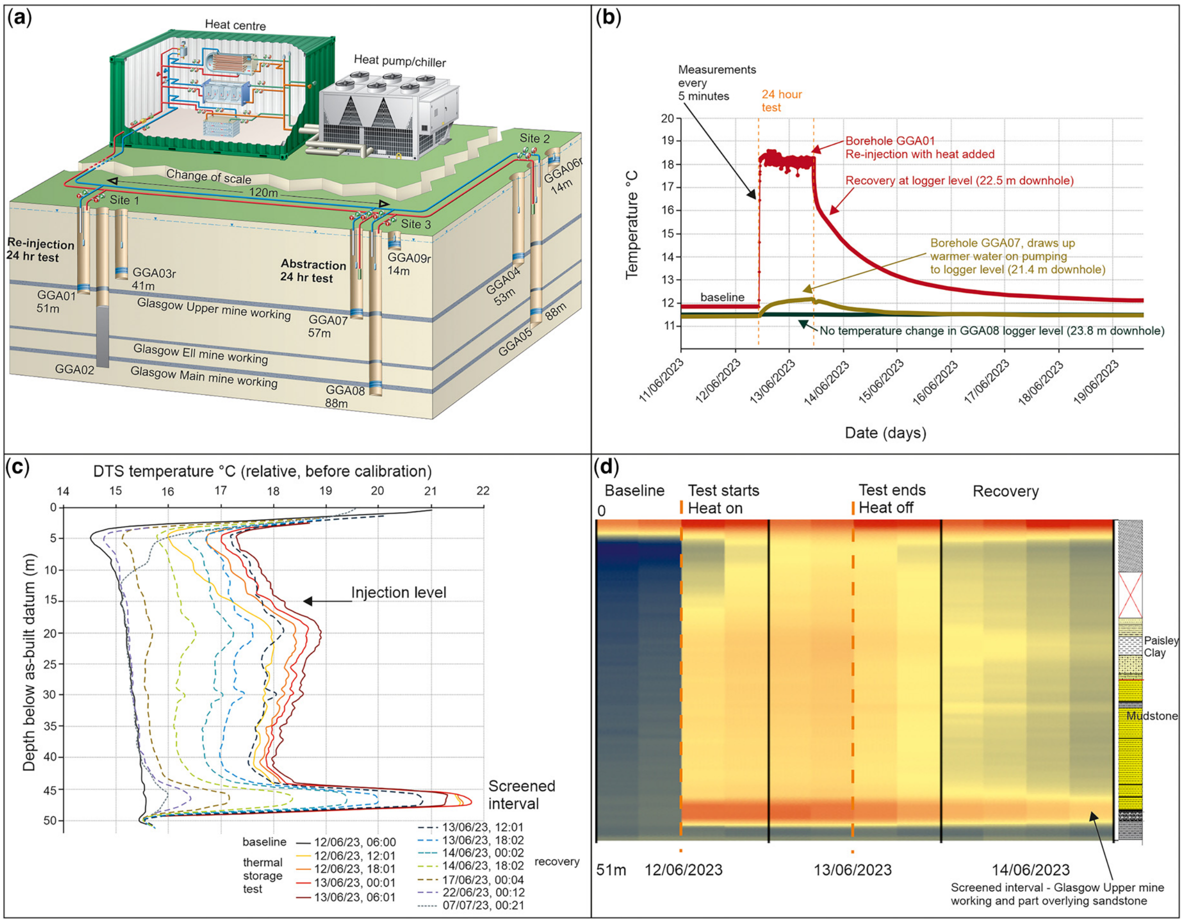

Fig. 5. (**a**) Schematic image of the geothermal infrastructure at the UK Geoenergy Observatory in Glasgow and nine of the boreholes located at Cuningar Loop. The known complexity of the subsurface is not shown, borehole casing depth below as-built datum are rounded to the nearest metre. Abstraction and re-injection boreholes for the 10.30 a.m. 12–13 June 2023 thermal storage test labelled. (**b**) Plot of the temperature measured in data loggers during the thermal storage test. (**c**) Measured (relative, before full calibration) DTS temperatures before, during and in recovery at certain times up to 24 days after the test in the re-injection borehole GGA01. (**d**) Time-series visualization of the DTS temperature data from re-injection borehole GGA01 before, during and after the thermal storage test with summary lithology downhole log shown on the right-hand side. Source: BGS © UKRI. Contains NERC materials © NERC 2024.

(to 6–7 m deeper; Figs 4 & 5a). Geochemical changes observed in borehole GGA01 between January 2020 and mid-2021 are interpreted to be caused by the oxidation of iron sulfide minerals (pyrite; Bearcock *et al.* 2022, 2023). Between July and December 2020 the warming–cooling curve in GGA01 of less than 1°C (Fig. 4) is comparable in size to calculated values for this exothermic reaction of 0.1–0.5°C per litre of water for the South Wales coalfield (Farr *et al.* 2016).

Geothermal commissioning tests

The relatively constant baseline temperatures can be contrasted with size and rate of temperature changes measured during commissioning of the geothermal infrastructure in spring/summer 2023. During a 24-hour thermal storage test, mine water was abstracted at 12 l s^{-1} from borehole GGA07 (screened section 50.91–53.61 m below the wellhead flange datum) at 11.8°C and re-injected in borehole GGA01 at *c.* 18°C (bottom of re-injection main at 15 m downhole, screened section at 44.81–48.41 m below wellhead flange datum, Fig. 5a), both boreholes are screened at the Glasgow Upper mine working. The hydrogeological data logger within a borehole screened at the Glasgow Main mine working in borehole GGA08 showed no temperature response as expected (Fig. 5b); the logger in GGA07 abstraction borehole recorded a slight rise in temperature (11.4 to 12.1°C) as mine water was drawn up to the pump and logger level from the deeper and slightly warmer screened mine working interval; and the logger in the re-injection borehole recorded the warmer water being re-injected and the temperature dissipating exponentially over a period of 6 days after the 24-hour test (Fig. 5b). The DTS fibre optic measurements capture more detail down the outside of the borehole casing and across the mine working screened section in GGA01. Figure 5c and d show the change from a linear downhole temperature trend pre-test, changing to temperature increase during the test with greatest magnitude of *c.* 6°C across the screened section.

For up to ten days during the recovery period, the influence of the geology on temperature recovery can be observed. Layers of clay within the superficial deposits and mudstone within the bedrock section retain slightly higher temperatures than surrounding strata (yellower stripes on Fig. 5d correlated to the lithology log, and bumps at *c.* 20 m and *c.* 30 m on Fig. 5c). This is interpreted to be due to the lower transmissivity and thermal conductivity of clay, mudstone (UK values 1.2–2.3 W m^{-1} K^{-1}, BGS 2020) compared to saturated sand, sandstone (UK values 2.5–6.5 W m^{-1} K^{-1}, BGS 2020).

An additional feature of interest is the +0.5°C temperature above the starting baseline at the screened interval measured 24 days after the test (Fig. 5c). The timescale of this thermal change contrasts markedly with pressure (water level) changes that recover within minutes of pumping stopping (Shorter *et al.* 2021).

Similar rates of change were observed on the DTS equipment during a 5-hour heat abstraction commissioning test from borehole

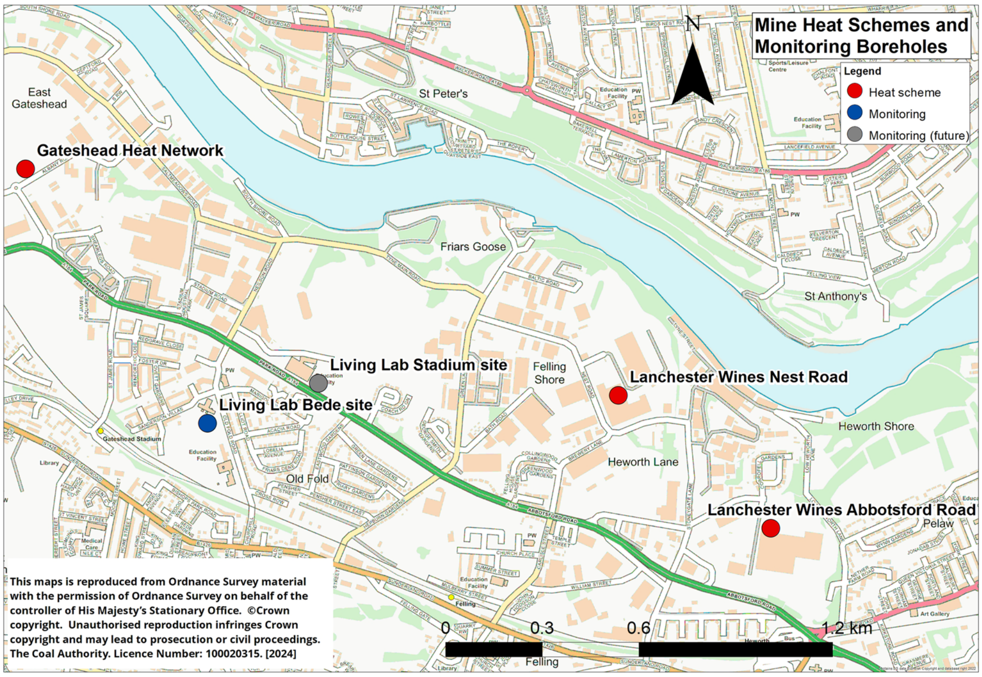

Fig. 6. Active mine water heat schemes and operational and planned monitoring boreholes for the Coal Authority Mine Water Heat Living Lab, located in Gateshead, NE England. All locations are approximate and for illustration only. Source: © Coal Authority 2024, reproduced with permission.

GGA07 to GGA08, showing the cooler groundwater re-injected. The temperature down the fibre optic cable in GGA08 decreased by around 1.5°C during the test, temperature recovery took around 2–3 days on the cable behind casing and adjacent to rock down the borehole. Recovery was quicker (a day or less) at the screened mine water interval, which in borehole GGA08 is an open roadway.

The initial 24-hour thermal storage test results show time–temperature changes along the length of the boreholes, including rapid changes of 0.4°C/hour (behind casing/rock) and 1°C/hour (at screened interval) in response to 12 l s^{-1} and ΔT of +6°C during pumping. During recovery, rates of heat depletion are around 0.1°C/hour initially, reducing over time and with notable influence of lower transmissivity and thermal conductivity clay and mudstone layers (Fig. 5d). These early insights from the short geothermal commissioning tests available in mid-2023 prove the concept of using highly instrumented infrastructure to characterize and quantify geological factors during mine water geothermal activities.

Mine Water Heat Living Lab at Gateshead

The Coal Authority Mine Water Heat Living Lab will be a first of a kind monitoring facility to observe the nature of and potential for thermal and hydraulic interactions between three at-scale, operational mine water heat schemes in the Walker mining block near Gateshead, NE England (Fig. 6). The mine heat potential in this area was initially exploited by Lanchester Wines who operate 2.4 and 3 MW$_{th}$ schemes that heat individual warehouses in Felling (Banks *et al.* 2022), then followed by Gateshead Energy Company who operate from 2023 a 6 MW$_{th}$ (peak) mine water heat network located around 1.5 km away at Gateshead. In this same area, the new Mine Water Heat Living Lab is generating data that may help to elucidate interactions between adjacent schemes, with a view to informing future licensing and permitting decisions when multiple schemes propose to operate in one mine water block. The intention is to facilitate more widespread uptake of mine water heat across Britain. Data collected from the Living Lab are open access and available to a range of stakeholders interested in developing mine heat resources (Coal Authority 2024). The data may also be of interest to the regulator (Environment Agency in this case) to examine the potential for interactions between adjacent users and any mixing or changes in mine water quality resultant from abstracting and re-injecting mine water from and to different mined seams.

Drilling at the Mine Water Heat Living Lab Bede site, Gateshead (Fig. 6; grid reference: 426781 562670) began in 2023 and, as of end 2023, two of four planned boreholes have been installed. Drilling for the remaining two boreholes will resume in 2024. The two boreholes at the Bede site intersect the Brass Thill (Bede Brass Thill) and High Main Seams (Bede High Main) at 136 and 56 m below surface, respectively. Key parameters being measured include water levels, temperatures and pore pressures plus electrical conductivity. The deeper borehole is equipped with several vibrating wire piezometers at different depths and fibre optics, both installed outside the borehole casing. Water samples will also be taken to observe any signs of mixing between water of different qualities from different levels in the mine. The deeper borehole is anticipated to monitor abstraction at the Gateshead Energy Company Scheme and some re-injection at Lanchester Wines and the shallower borehole is anticipated to reflect re-injection by Gateshead Energy Company and some abstraction by Lanchester Wines.

Initial data show responses in water levels linked to activities relating to the active mine water heat schemes. Responses in water levels have previously been observed whilst monitoring and testing the boreholes for the Gateshead Energy Company scheme and attributed to pumping taking place at Lanchester Wines (Banks *et al.* 2022). Thermal changes have not been detected in any monitoring boreholes as at late 2023. Data from both operational sites will be crucial in order to disaggregate the activities at each site and examine their impacts (if any) upon the measured parameters.

Conclusions

In the quest to reduce CO_2 emissions and decarbonize heating of buildings, re-use of disused flooded coal mines in the UK offers a proven technology for shallow geothermal heating, cooling and storage. As a decentralized, local heat source, thermal store or as the baseload to an integrated heating and cooling heat network, the technology has potential to increase energy security and resilience. With enhanced deployment of the technology at increasing scale, thermal load (ΔT) and repeated heat/cool/storage cycles, characterizing the magnitude and rate of subsurface heat-flow transfer processes and benefits/impacts on the wider environment become critical to sustainable management. For example, to avoid undesirable depletion or interaction of thermal resources, or unintended cumulative impacts on the environment.

Review and synthesis of the geological factors for sustainable management of mine water geothermal highlight many (hydro)geological and operational factors controlling temperatures and heat-flow processes, notably groundwater advection in mined aquifer systems, mine geometry, hydraulic connectivity and aquifer properties, together with pumping rates, timescales and thermal load. With the potential for commissioning multiple mine water geothermal schemes within the same area, understanding of the cumulative impacts of adjacent operations to water levels, groundwater flow directions, biogeochemical and geomechanical properties is important. Approaches for 3D spatial planning, such as thermal blocks, thermal protection zones or integration of heat/cool users, towards regulation and licensing of mine water geothermal resources, require an improved, measured evidence base to better understand the magnitude and rate of 'how far heat goes' and 'how quickly it is replenished or dissipated' to maintain a sustainable supply.

Early results from highly instrumented at-scale infrastructures for mine water geothermal (UK Geoenergy Observatory, Glasgow) and monitoring of adjacent mine water heat schemes (Living Lab, Gateshead) prove the concept of measuring, quantifying and visualizing baseline and induced heat-flow changes and processes. An example is given of a 24-hour thermal storage test, with rapid temperature changes measured in rock and the mine working, followed by dissipation and thermal recovery over a period of 3 weeks. Magnitude and rates of heat transfer are greatest at the screened mine working, with recovery in the rock mass influenced by lithologically controlled transmissivity and thermal conductivity.

Geothermal investigations and monitoring are in the initial stages at these at-scale, real world sites, but some key factors have been observed, such as differences in rates of hydraulic and thermal processes. Future work will further test, measure and quantify an improved evidence base to better understand the critical, sensitive and transferable geological factors and translate these to heat/cool/storage management approaches for mine water geothermal energy.

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Author contributions **AAM**: conceptualization (lead), data curation (equal), formal analysis (lead), methodology (equal), supervision (equal), visualization (lead), writing – original draft (lead), writing – review & editing (lead); **CAA**: conceptualization (supporting), writing – original draft (equal), writing – review & editing (supporting); **RAB**: conceptualization (equal), investigation (equal), methodology (equal), project administration (equal), supervision (equal), writing – review & editing (supporting); **MAL**: conceptualization (equal), investigation (equal), methodology (equal), writing – review & editing (supporting); **DB**: conceptualization (equal), data curation (equal), formal analysis (equal), visualization (equal); **AGQ**: conceptualization (equal), methodology (equal), writing – original draft (supporting), writing – review & editing (supporting); **VS**: conceptualization (supporting), data curation (supporting), investigation (equal), methodology (equal), supervision (equal), writing – review & editing (supporting); **GF**: conceptualization (supporting), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), validation (equal), writing – review & editing (supporting); **LMW**: conceptualization (supporting), methodology (equal), writing – review & editing (supporting); **FT**: data curation (supporting), writing – review & editing (supporting); **KW-V**: data curation (equal), formal analysis (equal), investigation (equal), methodology (equal); **DJM**: data curation (equal), investigation (supporting), methodology (supporting), supervision (supporting), validation (equal); **CA**: conceptualization (supporting), investigation (supporting), methodology (supporting), project administration (supporting), supervision (equal), writing – review & editing (equal); **BP-R**: conceptualization (supporting), investigation (supporting), methodology (supporting), writing – review & editing (supporting); **JS**: conceptualization (supporting), investigation (supporting), methodology (supporting), writing – review & editing (supporting).

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Data availability Open data from the UK Geoenergy Observatory, Glasgow are available via https://ukgeos.ac.uk/data-downloads or the National Geoscience Data Centre (https://www.bgs.ac.uk/geological-data/national-geoscience-data-centre/ and the baseline time-series, sensor data from https://sensors-gui.bgs.ac.uk/. The hydrogeology logger and DTS data illustrated in Figure 5 are provided as Supplementary information.

Open data from the Coal Authority Mine Water Heat Living Lab, Gateshead are available at https://www.data.gov.uk/dataset/0aab938a-07b5-4c95-9c11-1b09ac4e82da/gateshead-mine-water-heat-living-laboratory.

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