PhD Plan

Investigating geothermal heat resources of legacy mine workings, why are some mine waters hotter than others?

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Abstract

This PhD plan has been realized as a draft for the PhD confirmation report due by the 6-9th month from the start of the PhD.

[The Hook] Abandoned flooded coal mines in the UK represent low-temperature geothermal reservoirs that can potentially be used for heat storage or production (Adams and Younger, 2001). The presence of mining voids inherited from the extraction of coal seams in e.g. the Carboniferous layers of the Midland Valley of Scotland, has led to the formation of high-permeability reservoirs in which large volume of water are stored. Hot mine water therefore constitutes a low carbon heat source from which heat can be extracted using open-loop ground source heat pump systems.

[Knowledge gap] However, a little is known about the heat potential, the heat sources and the recharge mechanisms in mine systems (Coal Authority, Pers. Com., 2019). Temperature measurements in several shafts in the UK have shown the lack of correlation between the depth of the measurement and the temperature of the mine water (Gillespie et al., 2013). In addition to the regional geothermal gradient, it is suggested that other factors might contribute to defining the mine water temperature. The complexity of the interconnections between mine workings represents one of the most challenging barriers in understanding mines hydro-geology.

[PhD motivation] The conducted PhD research will therefore aim to understand the temperature distribution in the mines by identifying the main factors controlling heat recharge. A key outcome of this work will be the development of a predictive tool, model or conceptual approach that enables the scientific estimation of the extent and nature of the heat available over the long term in abandoned flooded coal mines.

Contents

1 Context

1.1 Research background

Abandoned flooded mines constitute potential low-temperature geothermal reservoirs that can be used for energy storage and production (Adams and Younger, 2001). Using mine-water as a source of energy has been of growing interest in the UK (Banks et al., 2004). Former mine workings, galleries, shafts and roadways indeed create an interconnected network of open voids that get flooded after the closure of the mine and the cessation of dewatering. This forms high-permeability "mine reservoirs" from which water can be extracted at relatively high rates (Banks et al., 1997). Moreover, most of the mining fields are located near densely populated area, giving the opportunity to provide local population with a low-carbon source of heating or cooling through the use of open-loop Ground Source Heat Pump (GSHP) systems (Małolepszy, 2003).

Mine water geothermal systems have already been implemented worldwide, such as Heerlen in the Netherlands (Ferket et al., 2011) or Mieres in Spain (Andrés et al., 2017; Loredo et al., 2017). In the UK, the first systems were implemented in Shettleston and Lumphinnans in Scotland in 1999-2000, providing heat to 16 and 18 dwellings, respectively (Banks et al., 2009). To mitigate the discharge of contaminated mine water to the surface environment, the Coal Authority has been responsible for the implementation of mine water treatment systems across the UK (Younger, 2004). About 3000 L/s of mine water are pumped from more than 50 abandoned coal mines, representing about 100 MW of potential low enthalpy heat energy (Banks et al., 2009).

A recent Scottish government study on the geothermal potential of Scotland (Gillespie et al., 2013) showed that about 1/3 of Scotland's heat requirement could be sourced from abandoned mine workings. In the UK and in Scotland, more than 1/3 of the energy consumed is used for space and water heating. Hydrocarbons (i.e. natural gas) covers more than 90% of the heat demand and thus account for most of the Greenhouse Gas emissions in the country. In 2019, the UK Government decided to focus on the decarbonization of residential heat to achieve the 'Net Zero' emissions target by 2050, accordingly to the 2019 UK's Climate Change Act. In this perspective, both the UK and Scottish governments agreed to replace all gas boilers by low-carbon heating systems in all new homes by 2025 (*Clean Growth - Transforming Heating* 2018). This represents a big challenge, requiring the development of new technologies and the access to new renewable/low carbon energy resources. Using mine-water as a heat energy source could therefore contribute to the challenging Scottish target to reach neutral carbon emissions by 2045 (Stark, 2019).

Mine-water based heat systems finally represent cost-effective geothermal systems. In addition to providing low-carbon energy, using mine-water as a source of energy could indeed give the opportunity to decrease costs associated with the maintenance of water treatment systems by selling heating or cooling services (Loredo et al., 2016).

1.2 Knowledge gap

To promote the development of heat extraction schemes, the Coal Authority wish to get a better understanding of the geothermal resources in mines, including their storage capacity and the sustainability of heat extraction.

Knowing the lateral extent of the area affected by heat extraction around a production well and the recovery rate (i.e. time for a mine system to recover its initial temperature when production stops) is also of primary interest as it could support the development of a methodology to guide the licensing of heat (Ian Watson, Coal Authority, Pers. Com. 2019).

However, a little is known about the source of heat in coal mines and the recharge mechanisms induced by heat extraction. The 2013 AECOM report (Gillespie et al., 2013) showed a significant variation in the temperature of the mine water down to about 1500 m depth, with no apparent correlations between the depth of the measurements and the fluid temperature, indicating that other factors than the geothermal gradient might contribute to the definition of the mine-water temperature.

The main purpose of this PhD is therefore to understand the subsurface heat distribution of mine workings and determine what are the main factors controlling the near subsurface water temperatures in a more regional context. Those elements are critical to assess realistically the heat resource and storage potential in mines.

2 Research field

2.1 Research question

The topic of the PhD relates to the "conceptualization of mine water temperatures", aiming to answer the general PhD research question: "why do different mines have different temperatures?"

2.2 Research aim and objectives

The aim of the research project is to get a better understanding of the temperature distribution in flooded mine workings and of the main factors controlling mine water temperature. This will be used to assess the heat recovery potential and thus the sustainability and heat storage capacity of mine reservoirs. The research project includes three main objectives.

- Create hydro-geological conceptual model(s) of flooded coal mines reservoirs to identify what are the main controls on temperature in mines. This conceptual model will consider the relative contribution of different heat sources and the dominant heat transfer mechanisms. An inventory of the data available for different coalfields in Scotland (i.e. geological structure, water temperature, discharge) and of the mine structure will be performed to get an overview of the potential hydro-geological structures.
- Develop a numerical tool (i.e. 3D model) able to predict the steady state mine-water temperature (i.e. if temperature equilibrium is reached in the mine before heat production), as well as the changes in the production temperature with time due to heat extraction from GSHP systems. This tool will aim to predict the extent of the area impacted by heat mining around the production well and the rate of energy recovery once extraction is stopped. One or two mines will be selected as case studies to develop and validate the model.
- Determine the external energy input (i.e. injection of heat of heat from other sources) necessary to create a sustainable heat reservoir in flooded coal mines, using energy balances and numerical simulations.

2.3 Take home message

Flooded coal mines constitutes potential low carbon heat energy resource. However, the sustainable use of heat from coal mines can only be achieved with an appropriate dimensionning of GSHP systems, which only depends on the good understanding of the heat capacity and recharge mechanisms of the underground. A key outcome of this work will be the development of a predictive tool, model or conceptual approach that enables the scientific estimation of the extent and nature of the heat available over the long term from abandoned flooded coal mines in the UK. This tool could be used to support the design of mine-water based heat extraction schemes, the assessment of sustainable production rate, but also guide the licensing of heat with a scientific approach.

3 Research design

3.1 Methods

Existing data (i.e. discharge and/or pumped water temperature, temperature profiling, conductivity logs, discharge rate, heat flux estimates, fluid geochemistry analysis) will first be collected and classified according to their location (i.e. coalfield, mining area) and context of the measurements (i.e. flooding conditions, gravity-driven discharge, pumped water). The monitoring sites will be put into their geological context using geological, structural maps and cross-sections, to evaluate the possible contribution of local heat sources / recharge areas on the measured temperature (i.e. presence of fault, type of rocks and volume of rock type around the monitoring point). In areas where flooding is still occurring, changes in fluid temperature or geochemical composition through time might be used as an indicator of the existence of significant interconnections at specific mine levels. Detailed mine abandonment maps for specific areas will be analyzed and compared to the geological and monitoring data to identify potential connections between the mine workings/shafts and recharge/discharge zones at the surface or with surrounding aquifers.

This preliminary work will be used to develop hydrogeological conceptual model(s), considering different typical mine geometries and geological context (i.e. horizontal layers, dipping layers, syncline), and the potential heat sources.

For each scenario, numerical tools will subsequently be used to demonstrate the influence of natural heat flow, local heat sources as well as local/regional groundwater flow and convective flow in highly connected subsurface void on the mine temperatures. The impact of solar input and its yearly fluctuations will be of particular interest. Sensitivity analysis will be performed to assess the relative importance of a series of parameters and boundary conditions on the pumped/discharged water temperature. This analysis will allow the assessment of the main transfer mechanisms in mines and the relative contributions from each of the heat sources.

Calibration and validation of the model will be performed using data from naturally gravity-driven discharge areas and from pumped water. While water naturally discharging on the surface might be representative of steady-state conditions in the mine (i.e. water reaching temperature equilibrium with the mine rock after the end of the flooding period), pumping implemented to maintain water level below the ground surface might induce turbulent flow and mixing, disturbing the natural temperature conditions. In the latter case, simulations will allow determining if a steady state can be reached in the mine if no heat scheme is implemented.

A comprehensive comparative study between two mining areas will then be performed, based on 3D numerical simulations of flooding, heat extraction and heat recovery stage. Results will be used to estimate the area impacted by the extraction of heat, the time necessary for recovery, but also to assess the total heat capacity of the mine. Based on the local energy demand, those elements will be used to evaluate the optimal GSHP system allowing to main long-term and sustainable heat recovery / storage from the mine reservoir.

3.2 Case study

The preliminary analysis will first focus on the collieries of Midlothian coalfields (Fig. 3.1) and will be extended to further coalfields where sufficient data is available or in areas where heat extraction schemes are or will be implemented.

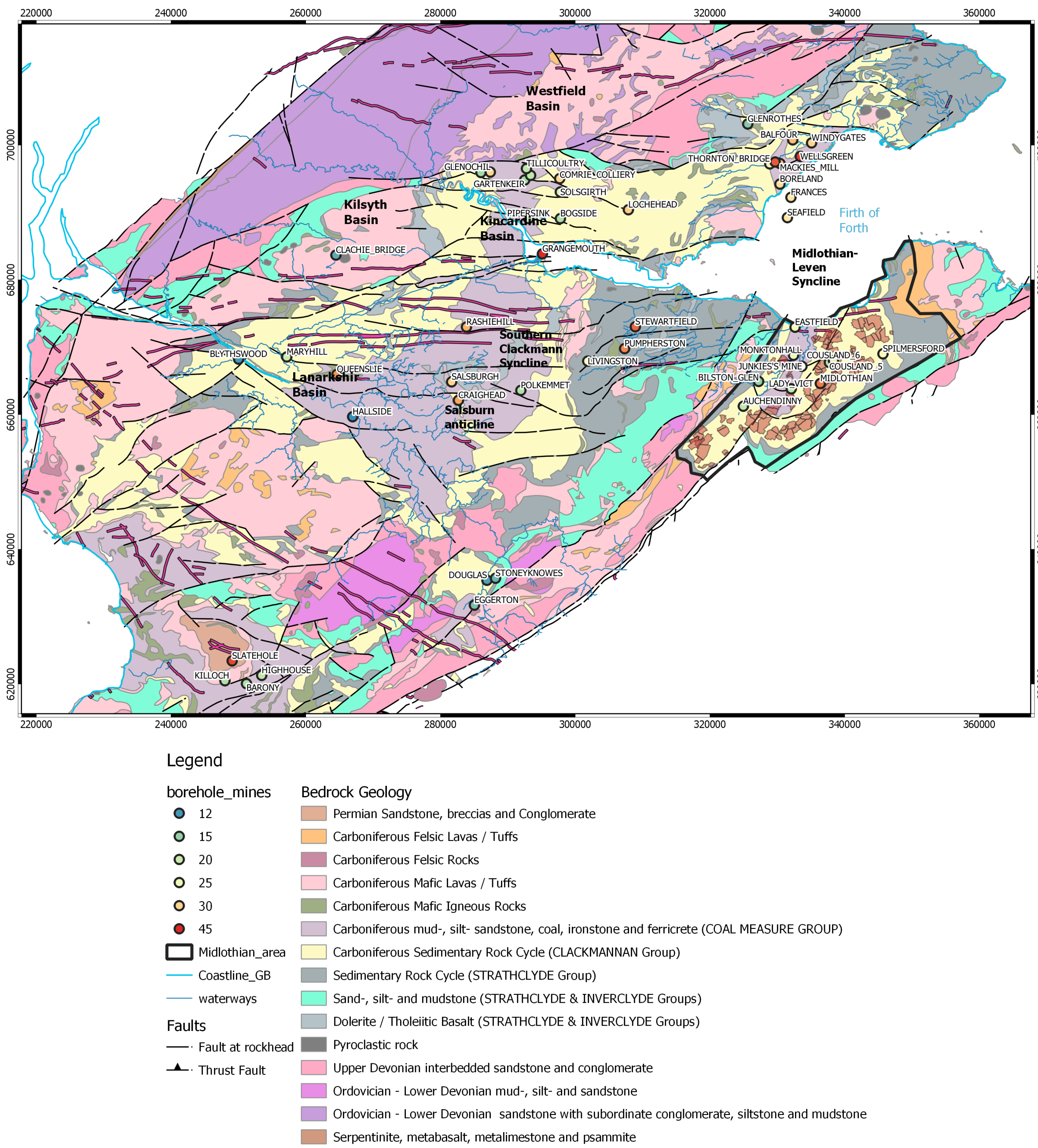

Figure 3.1: Geological map of the Midland Valley of Scotland

3.3 Data sources

Several factors need to be considered to understand the temperature distribution in mines. This includes the natural heat flow, the presence of local heat generation (i.e. radioactive day, pyrite oxidation), solar influx, the impact of groundwater flow and geological structure (i.e. geological formation with specific material, thermal and hydraulic properties, faults) and the connectivity and extent of mine workings.

The data will include information from in situ sensors, seasonal data, legacy data available in various archives and geological data.

Data available in the archives and database at the Coal Authority includes:

- Layers of Data visible at http://mapapps2.bgs.ac.uk/coalauthority/home.html, and that can be downloaded under a license agreement with the Coal Authority (except unlicensed data older than 25 years)
  - Shafts (geometry and current state)
  - Underground workings (seam codes, thickness, type, depth), based on 1 km x 2 km digitalized mine plans. A 3D view is available for the Bilston Glen Shaft
  - Spotheight: seam level (floor level, OD)
  - Roadways (may represent major flow path at the bottom of shafts).
  - Monitoring points (outflow, temperature)
  - Coal seams outcrops
  - Geological disturbances
  - Shallow coal (<30 m), with buffer indicating areas with collapse hazards (i.e. Blindwells site: opencast in East Lothian Coalfield)
- Mine abandonment Plans (nVision internal system at the Coal Authority), containing more details on the mine architecture.
- Monitoring data: data available at 260 locations currently being reported in a Summary Excel Sheet, containing the minimum/maximum temperatures at each site, the flow rates at shafts, the depth to water...
  - Temperature
    - Temperature versus time (i.e. Junkies outflow). Continuous logging is only done at a few sites.
    - Temperature and conductivity logs, sometimes repeated through time.
    - Water level logger: inform on the temperature at the depth of the sensor but is not associated to information about the depth of the sensor. Can inform on seasonal changes in temperature.
    - Manual measurements
  - Pumping tests

Historical geological, temperature and dewatering data can also be obtained from old reports (Burley et al., 1984), from the former private Coal Mining Companies and new research papers.

The Glasgow Geothermal Energy Research Field Site moreover constitute since 2018 an additional source of data, specifically acquired to improve the understanding of the geothermal potential of abandoned flooded mine workings below Glasgow.

Additional long-term measurements of temperature, discharge and water geochemistry at several monitoring site located within the selected case study areas might moreover be useful to validate the models.

Detailed geological maps, cross-sections and geological well logs/core analysis will also be collected from British Geological Survey (BGS) databases.

If not available yet, the acquisition of micro-gravity and resistivity data might help identifying the presence of density contrasts in the reservoirs, indicating heterogeneities such as granite intrusions, potentially representing sources of local heat production.

3.4 Data analysis

Open-source GIS tools (i.e. QGIS) will first be used to analysis the spatial distribution of the data, create maps and perform cross analyses.

Numerical calculations will be performed using OpenGeoSys, an open source code developed to solve for coupled thermo-hydro-geomechanical-chemical (THMC) processes in porous and fractured media (Kolditz et al., 2012).

Modeling results will be visualized and post-processed using Paraview and Tecplot.

Python scripts will be used for additional data processing and data visualization.

4 Chapters

4.1 Chapter 1

4.1.1 What we know

Minewater temperatures reported in the BGS Catalogue of Geothermal Data for the UK (Burley et al., 1984) were analyzed by Gillespie et al., 2013. Temperatures measured from nine boreholes in the Midland Valley of Scotland (MVS) range from 12 to 21°C, with a mean/median of 17°C. The average temperature for water circulating above 200 m depth has been reported to range between 8 and 15 °C (Robins, 1990). Despite the temperature of waters generally increases with depth according to the geothermal gradient, no correlation has been found between the depth of the measurements and the mine water temperatures in the MVS. In 2008, groundwater samples were collected as part of the Scotland Baseline Project from boreholes abstracting water from Carboniferous sedimentary aquifers across the MVS (Farr et al., 2016). Four of them originate from abandoned flooded mine workings, either pumped or from gravity-driven discharge zones. Temperatures of two of the measured pumped mine-water were 11.7 and 14.5 °C, in accordance with the typical temperature of natural groundwater from Carboniferous aquifers in the MVS. Temperature of the sampled mine-water pumped from the Polkemmet mine shaft was 19.2 °C, while the measured temperature of the gravity-driven discharged mine-water was 9.8 °C. Farr et al., 2016 and Burnside et al., 2016 also reported average temperatures of 11.5-13.3 °C and 14-15 °C for the Crynant, Dulais Valley, South Wales Coalfield and the Caphouse Colliery, respectively.

4.1.2 Knowledge gap

- The cause for the differences in mine water temperatures across Scotland.
- A comprehensive study of the relative contribution of different heat sources in areas such as the Midland Valley of Scotland, where no apparent geothermal potential exists.
- The heat depletion, recovery rate and extent of the area affected by heat mining.

4.1.3 Research Question

What are the main sources of heat and heat transfer mechanisms controlling the temperature distribution in mines?

4.1.4 Hypothesis

- H0: The steady state temperature in mines of the MVS, if it can be reached, mostly depends on the local geothermal gradient (conductive heat transfers in porous medium), on the extent of gravity-driven mixing in open voids (i.e. shafts) and on the number/thickness of low-conductivity coal seams.

- H1: The rate of temperature change of the extracted water mainly depends on the hydraulic conductivity of the mine voids, on the production rate and the distance from re-injection.
- H2: The recovery rate is mainly influenced by the thermal properties of the rock, the presence of local heat sources (i.e. radioactive decay, geochemical reactions) and recharge areas (i.e. river infiltration,fault).
- H3: The measured minewater temperature are not representative of the reservoir conditions (i.e. lack of information about the measurement conditions).

4.1.5 Methods

- Cross-correlate the existing temperature measurements (e.g. temporal monitoring or profiles) with contemporary discharge/pumping rate and fluid chemistry, looking at the location of the monitoring site, the geological structure, the volume of surrounding rock of different types, the historic rock temperature measurements and the flooding/dewatering history of the mine. This will be done to identify the potential contributions of local hydrological structures on the discharged/pumped temperature and the possible sources of heat, by creating maps and cross-sections in GIS software.
- Create conceptual model(s) based on typical geological structure and/or mine architecture (i.e. Fig. 4.1).

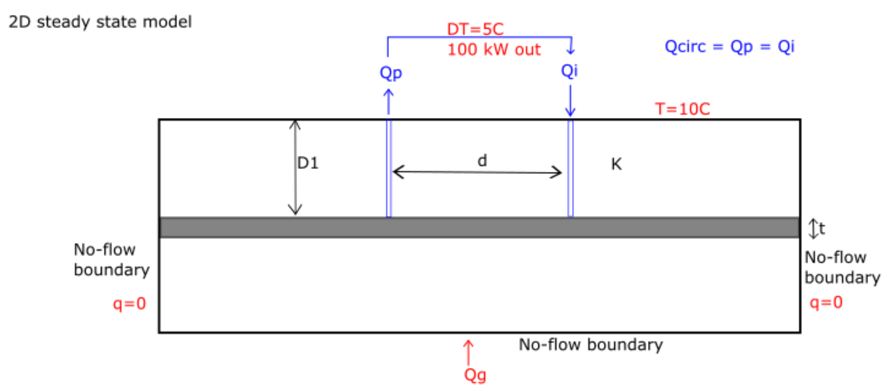

Figure 4.1: Simplified 2D Conceptual model of a mine gallery (longwall panel)

- Using 2D numerical models, perform a sensitivity analysis to evaluate the impact of geometrical parameters (i.e. number of coal seam mines, presence of roadways/shaft, vertical and lateral interconnections between galleries), rock properties (i.e. thermal and hydraulic conductivity of surrounding rock and mines voids), source terms (i.e. radioactive decay, pyrite oxidation) and boundary conditions (i.e. infiltration rate, connection with surrounding aquifers) on pumped/discharged water temperature, based on the different conceptual approaches. For each case, the steady state temperature (i.e. once flooding is completed), the change in temperature under production (with and without re-injection) and the heat recovery rate will be simulated.
- Highlight the existence of mixing of water of different temperature/chemical composition and its potential impact on the surface environment, geothermal infrastructures (i.e. GSHP) and on the production temperature (i.e. temperature equilibrium in the shaft).

4.1.6 Output

- Geological cross sections with locations of temperature measurements.
- Conceptual model(s) with steady steady temperature profiles, if reached (i.e. Fig. 4.2).
- Analysis of the sensitive geometrical, technical or numerical parameters and assessment of the typical values for modeling mine-water temperature.
- Conclusion on the recommendations to build representative conceptual/numerical models of complex mines (i.e. important parameters, amount of simplifications of the mine workings geometry possible).

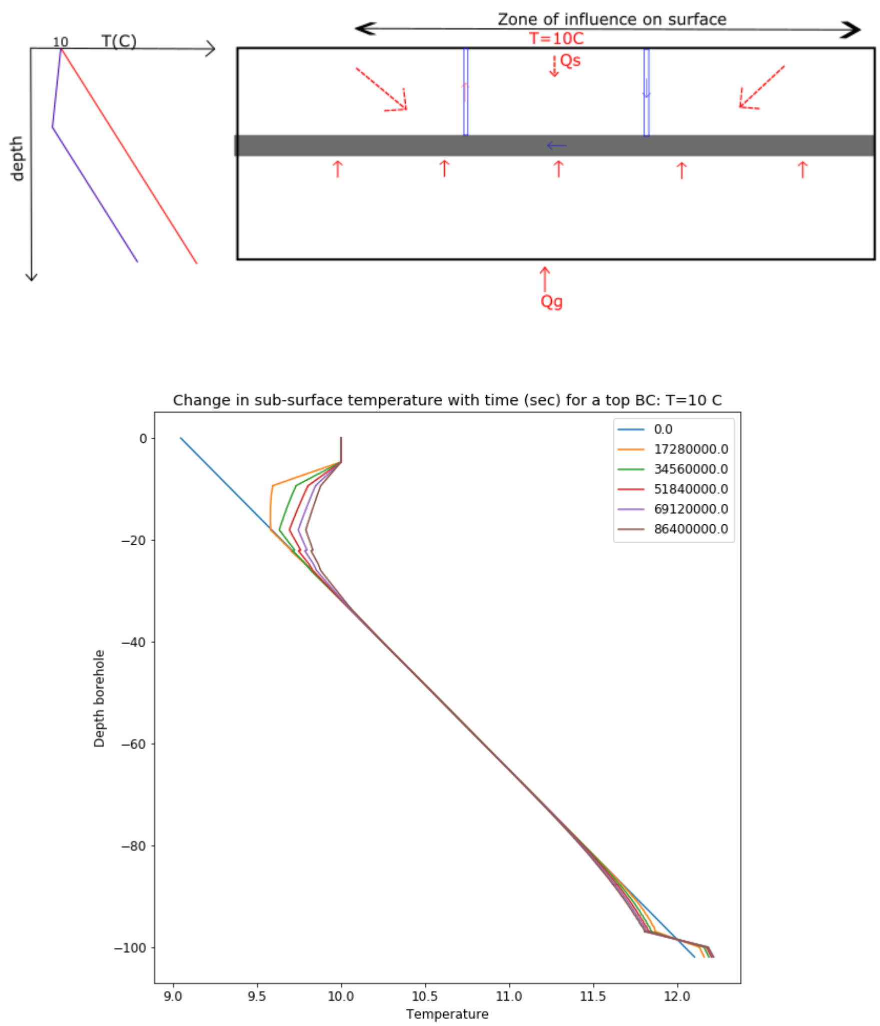

Figure 4.2: Example of steady state temperature results obtained from the conceptual approach 1

4.1.7 Anticipated results

If conductive transfers are dominant, then the presence of local heat sources (i.e. radioactive decay) and low-conductivity layer might contribute to local heat anomaly and greater heat recharge capacity.

If convective flow is dominant (i.e. gravity-driven mixing, high-velocity groundwater flow, high recharge rates), then the overall mine temperature might be lower and the heat depletion rate higher, especially at higher production rate.

4.2 Chapter 2

4.2.1 What we know

Mine aquifers are characterized by a triple-porosity composed of the primary rock porosity, the mining voids (i.e. galleries, shafts, roads. . .) and mining-induced fractures (Wolkersdorfer, 2008). After the closure of the mine, some galleries may be filled or partially filled by collapsed roof material and the former shafts may be backfilled and capped. Many shafts, roadways or drifts however remain as open and interconnected voids (Younger, 2001). These voids tend to form zones of high permeability in the mine, altering the natural groundwater flow within aquifers of initial low hydraulic conductivity. Unmined coal-bearing strata in the coal measures indeed form complex multi-layered minor aquifers, laterally and vertically compartmentalized through the presence of low permeability layers (i.e. mudstone) in between sandstone aquifers, igneous rocks (dykes, sills, plugs) and faults.

In mine reservoir modeling, the main difficulty arises from the necessity to solve simultaneously for heat transfer and mass flow within open pipes (i.e. galleries, roads, shafts), porous matrix (i.e. undisturbed reservoir rock with lower hydraulic conductivity) and fractures (Ferket et al., 2011; Renz et al., 2009). Predictions of groundwater flow in the coal measures is moreover limited by the lack of data associated to early mining and uncertainties about potential hydraulic connections. Despite no standard modeling approach has emerged yet to predict both the temperature changes and the absolute thermal capacity of mines (Renz et al., 2009), different methods have been used in the literature to solve for heat transfers and fluid flow equations in mine systems, using analytical models (Rodríguez and Díaz, 2009), numerical models (Loredo et al., 2016), or a combination of both (Renz et al., 2009; Ferket et al., 2011). Analytical models solve for the exact mathematical solutions of flow and heat transport by considering homogeneous systems, and therefore require geometrical simplifications (Banks et al., 2009; Loredo et al., 2017). Numerical models allow creating more realistic representations of mining scenarios but require more data and computational time, which make them more complex to use. In addition, such complex model might be subjected to numerical instabilities, limiting their reliability (Renz et al., 2009).

Based on previous studies, abandoned coal mine reservoirs can be divided in two main domains:

- The mine voids (i.e. tunnels), modelled as heat exchangers of simple geometry from which the heat flow and temperature change can be estimated by semi-empirical method/analytical solutions or numerical models (Ghoreishi-Madiseh et al., 2012).
- The mined area or goaf, consists of an area of complex geometry composed of fractures and secondary porosity, closely related to the mining method and the roof conditions. Studies include the modeling of heat transfers in longwall panels (Ghoreishi-Madiseh et al., 2015).

More specifically, numerical strategies developed to predict temperature evolution in a mine reservoirs include:

- The assimilation of the mine as a porous medium with different hydraulic conductivities in which Darcy flow is considered for both host rocks and workings (Małolepszy, 2003; Guo et al., 2018; Hamm and Bazargan Sabet, 2010; Malolepszy et al., 2005; Andrés et al., 2017)
- The hybride finite element mixing cell approach described in Brouyere et al., 2009.
- The use of 3D Navier strokes calculations (Wolkersdorfer, 2008) to model both laminar flow within 3D porous media and turbulent 1D pipe flow in mining voids (Raymond and Therrien, 2008).

4.2.2 Knowledge gap

- The heat capacity and potential area impacted by heat production at XXX and XXX (2 case studies).
- The best approach to create reproducible 3D model set-up and modeling strategies for estimating the total heat capacity, temperature changes and rate heat recovery in flooded coal mines of complex geometry.

4.2.3 Research Question

How sustainable is the extraction of heat from mines? Can we reliably predict the temperature change that will result from a fixed amount of heat extraction?

4.2.4 Hypothesis

- H0: The area influenced by heat mining mostly depends on the geometry of the mine.
- H1: the temperature change and recovery rate can be predicted using numerical tool based on appropriate conceptual models.
- H2: The void volume and total heat capacity of a mine can be estimated by combining flooding/recovery data and simulation results, using reliable assumptions/simplifications.

4.2.5 Methods

- Develop 3D numerical models for 2 mines, based on the mine abandonment plans and geological structure.
- Calibrate the model by simulating water recovery during flooding of the mine, based on the flooding/dewatering history, the discharge rate and discharged/pumped water temperature over time. Temperature profiles and conductivity logs might also be used to verify the consistency of the geometry of the model (impact of mine workings layering, interconnectivity), identify potential recharge zones at depth and the contribution from each of them in the total water take.
- Based on the simulated steady state temperature after the termination of flooding, simulate the temperature change due to production for different production scenarios.
- Simulate the heat recovery time after the cessation of heat extraction/injection.

- Compare results with simplified models.

4.2.6 Output

- Assessment of the extent of area influenced by heat mining, at the scale of the shaft, working and/or of the whole mine.
- Validation of the predicting tool in supporting/guiding the licensing of heat in the study area.
- Conclusion on recommendation for the licensing of heat.
- Estimation of the total void volume/water content in the mine based on the simulation of flooding and the total heat capacity of the mine.

4.2.7 Anticipated results

If the simulation results match the monitoring data, then the predictive modeling tool can be validated.

4.3 Chapter 3

4.3.1 What we know

Mine-water based heating system generally operates in open-loop systems using Ground Source Heat Pump (GSHP) (Farr et al., 2016; Hall et al., 2011). In open-loop systems, the 12-20°C water pumped from flooded mine shafts and galleries circulates through a heat pump-heat exchanger unit before being discharged to a water treatment system (e.g. Caphouse Colliery, UK, Burnside et al., 2016), to surface water ponds (e.g. Mieres, Spain), or back to the mine via another borehole or shaft (e.g. the Shettleston and Lumphinnans, Scotland, Banks et al., 2009). In a standing column arrangement, the water is reinjected back the mine at a different depth through the same shaft after its passage through the HP exchanger unit (e.g. Markham Colliery, Bolsover, UK, Athresh et al., 2015). Open loop systems generally have high efficiency of thermal exchanges compared to closed-loop systems as the heat carrier fluid directly enters into contact with the surrounding hot rock (Luo, 2014). In a closed loop system, a calorific fluid circulates through a heat exchanger submerged in the flooded mine void, via a heat pump (e.g. shaft of Folldal Mine, Norway, Banks et al., 2004; minewater treatment lagoon, Caphouse Colliery, UK, Burnside et al., 2016; Banks et al., 2019).

The total volumetric heat capacity of a mine $E\,(W)$ mainly depends on the available water volume in the flooded mine voids $V\,(m^3)$ and on the mine-water temperature distribution, such as:

$$E = V\,T\,\rho_b\beta_b$$

where $\rho_b\beta_b$ represents the bulk volumetric heat capacity of the wet rock. The potential available heat energy that can be extracted from mine water using heat pumps will in addition depends on the water abstraction rate $Q\,(m^3/s)$, on the re-injected water temperature and the heat demand in the vicinity of the mine (Ordonez et al., 2012; Banks, 2016). This extractable energy rate (E_{h_p}) can be calculated as:

$$E_{hp} = Q\,\Delta T\,\rho_w\beta_w$$

where ΔT is the temperature change across the heat exchanger, and $\rho_w \beta_w$ the volumetric heat capacity of water (Raymond and Therrien, 2008). Regulations impose that the temperature difference between the extracted and injected water is lower than 8 °C and that the outlet temperature does not exceed 25 °C (Environmental Agency, 2012).

When thermally spent water is reinjected back to an underground reservoir, temperature will be progressively recovered by the water as it is flowing toward the extraction well. Conductive and convective heat processes triggered by the introduction/extraction of energy generally induce progressive cooling of reservoir rocks with time. Accurate estimates of the thermal breakthrough time and sustainable rate of heat extraction, which corresponds to the maximum rate at which the wanted COP can be maintained (generally in the order of 4) is therefore essential to assess the technical and economical sustainability of open-loop ground source heat pump systems (Ghoreishi-Madiseh et al., 2015).

Raymond and Therrien, 2008 used a simplified energy balance calculation based on estimates of the extractable energy rate (E_{hp}) and of the captured energy rate (E_c) to assess the geothermal potential (J) of the Gaspé Mine, Canada. The energy rate that can be captured by the pumping well was determined by multiplying the areal extent of the zone affected by pumping well, determined from multiple drawdown simulation predictions, by the heat flux. The sustainable energy production rate was here assumed to represent the pumping rate at which $E_{h_p} = 2E_c$.

4.3.2 Knowledge gap

- The total heat resources and amount of energy that can be extracted durably (i.e. for 30 years) from previously studied mine systems (i.e. Chapter 2).
- The storage capacity of the mine reservoirs and energy input that would be required to maintain constant temperature in the reservoir.

4.3.3 Research Question

Can heat from mine-water be extracted at a sustainable rate to match the local demand? What is the storage capacity of mine reservoirs and to which extent can they be used to increase the viability of heat extraction schemes?

4.3.4 Hypothesis

- H0: Heat extraction from mines cannot be sustainable without external energy input to the system.
- H1: When seasonal production is performed, a new steady state temperature can be reached, allowing to maintain the COP of the mine-water based GSHP system.
- H2: Mine-reservoir utilization can be improved and sustained when integrated into a larger energy grid.

4.3.5 Methods

- Estimation of the available/extractable heat using GSHP system, of the sustainable heat extraction rate and of the local heat demand, using previous 3D numerical models (Chapter 2).

- Run new simulations to assess the energy input required to maintain constant temperature in the mine and the optimal geometry of the system (i.e. sensitivity analysis), considering that the mine system is integrated into a larger energy grid (i.e. geo-battery).

4.3.6 Outputs

- Assessment of the main thermal processes and heat recovery rate to support the dimensionning of ground source heat pump system and their integration within larger scale energy grids.

- Suggestions for policies related to the licensing / extraction of heat.

4.3.7 Anticipated results

If heat can be maintained in the reservoir (either using seasonal production or external energy input such as heat from Data Centers), mines can be used as both storage system and heat source for GSHP systems.

4.4 Supplementary material: suggestion for a first paper

4.4.1 What we know

Solar input and surface air temperature, together with their seasonal and long-term (i.e. 10 000 years cycles) variations, have an influence on the pattern of the shallow subsurface temperature profile.

4.4.2 Knowledge gap

- The amplitude of the variations of heat flux required to fit the actual temperature gradient in the upper 15 m below ground surface.

- The depth of the zone where the geothermal gradient is disrupted by climate warming from the last glacial period in the MVS.

4.4.3 Research Question

What is the value of the surface heat flux that need to be used as surface boundary condition in heat models, to characterize the shallow geothermal gradient ?

4.4.4 Hypothesis

An yearly fluctuation of the mean surface heat flux of $\pm 0.1 W/m^2$ is required to reproduce the shallow subsurface temperature profile.

4.4.5 Methods

1D modeling of vertical heat transfer using varying heat flux as surface boundary conditions:

- Create a series of input files representing annual sinusoidal variations in heat flux, with different maximum amplitude (daily time steps).
- Use those files as surface boundary condition for the 1D model and run the model for 30 years.
- Analyse the resulting sub-surface temperature gradient.
- Repeat this process for each input file until the simulated temperature profile matches the expected real one.

4.4.6 Outputs

- A quantification of the absolute variations in surface heat flux.
- A 1D temperature profile of the upper 15 m.

4.4.7 Anticipated results

A maximum and minimum of $0.1\,W/m^2$ or 25 °C in summer and $-0.1\,W/m^2$ or -10 °C in winter are required as surface source term / boundary condition, respectively, to produce the observed sub-surface temperature profile.

5 Data management plan

5.1 Data repositories

File path	Usage	Description
C:	Desktop local space	Modelling and data processing
M:	Personal drive	General/administrative documents
R:	Research data store	Data, GIS projects, modeling results/analysis, scripts and bibliography (i.e. scientific papers, reports, books)
GitHub	Online university account	Storage repository and version control for reports (i.e. PhD plan, literature review, meeting reports), scripts and figures
Google Drive	Personal drive	Administrative documents and temporary notes
Overleaf	Online university account	Document redaction (i.e. reports, PhD plan)

Table 5.1: Data management

5.2 Codes

Scripts will be available from a public GitHub repository (see Tab. 5.1).

5.3 Version control management plan

The combined use of GitHub and GitHub Desktop on both personal and university computer will ensure the safe update and versions control of the PhD documents and scripts (see Tab. 5.1). In addition, the publication of a website with Github will facilitate the sharing of these documents / data with the supervisory team.

6 Time plan

The first year will involve the data collection of available mine water temperature data from the Coal Authority and other sources, and then investigate the key controls on mine water temperature. The second and third year will progress through the development of numerical modelling of temperature profiles and the interpretation of the results particularly with relevance to scoping out the size of the temperature resources available to use (see general and detailed timeline in Tab. 6.1 and Fig. 6.1, respectively).

Time period	Activities
2019 autumn	Preliminary tests, OGS learning and first modelling tests for Paper 1
2020 winter/spring	Data collection/analysis + Paper 1
2020 summer	2D Modeling of mine reservoir
2020 autumn	Results analysis + Paper 2
2021 winter/spring	Case study analysis
2021 summer	3D modeling and interpretation
2021 autumn	Predictive modeling tool validation
2022 winter	Paper 3
2022 spring	Modeling of sustainable mine reservoir system
2022 summer	Results analysis + Paper 4
2022 autumn	Thesis compilation
2023 winter/spring	Thesis conclusion + PIP?
2023 summer	Thesis submission

Table 6.1: General timeline

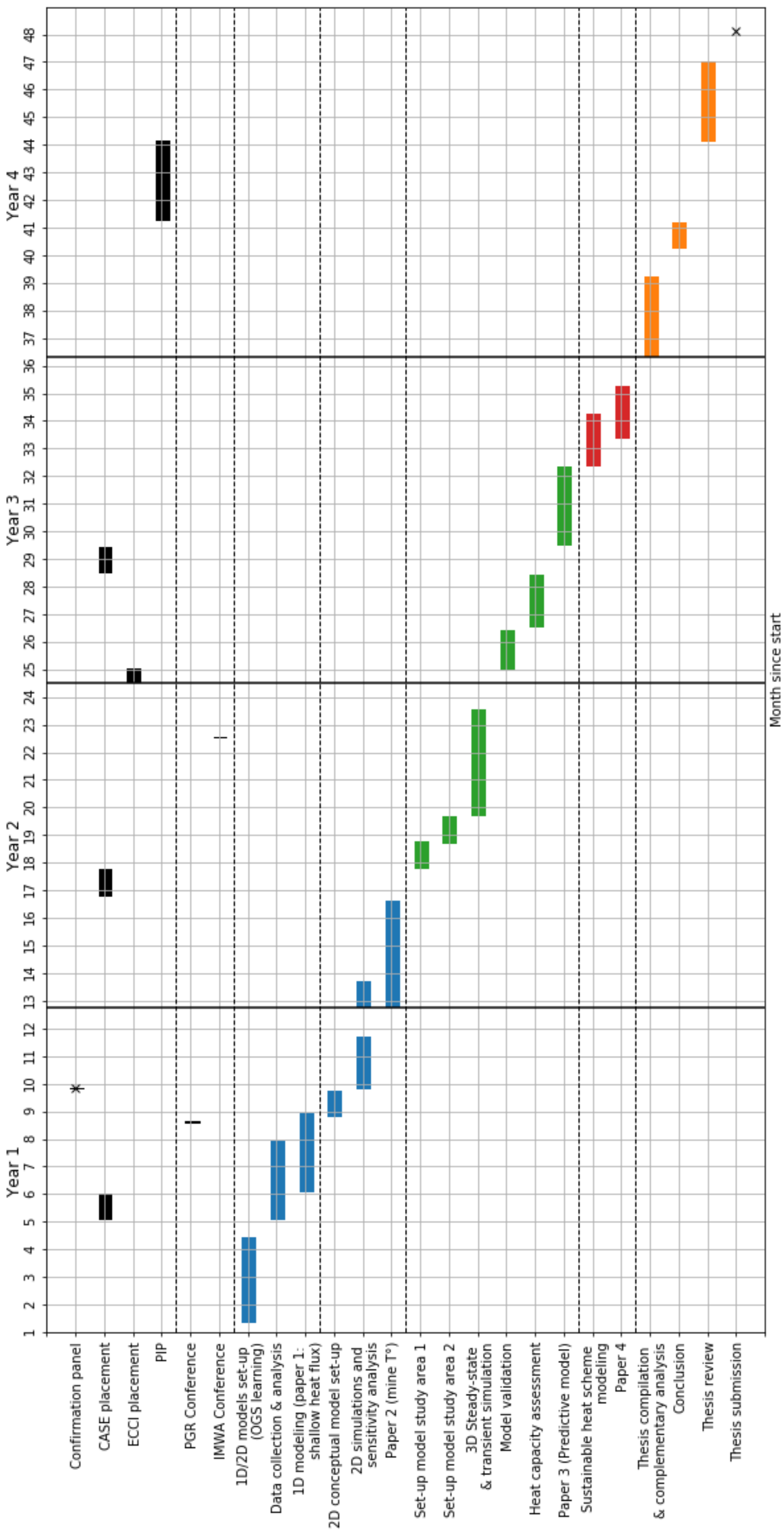

Figure 6.1: GANTT chart

7 Supervisory arrangements

- Principal supervisor : Christopher McDermott (University of Edinburgh)
- Co-supervisors (University of Edinburgh):
  - Andrew Fraser-Harris
  - Stuart Gilfillan
- Advisor: Wyn Williams (University of Edinburgh)
- External Advisors:
  - Ian Watson (Coal Authority, CASE sponsor)
  - Andrew Gunning (RSK)
- External collaborators: David Banks (Holymoor Consultancy Ltd)

8 Resources and Training

8.1 Training need analysis

Skills / training required	Courses / resources identified
Couples TH modelling (OGS)	Hydrology 2 (self-directed learning)
Hydrodynamics / Geothermics in mines	Journal / books (self-directed learning)
Python	NMDM course (E4 DTP training, self-directed learning, Datacamp courses)

Table 8.1: Skills and formations required

8.2 Teaching experience

- Hydrology 1 (Tutor, semester 1)
- Hydrology 2 (Tutor, semester 2)
- Earth Dynamics (Field demonstrator, Semester 1)

8.3 Conferences

Conference name	Date	Organiser	Location
UK 7th Geothermal Synopsium	Nov 2019	Geological Society London	London
Career and Industry Days	4 Dec 2019	Geological Society London	Edinburgh
GradSchool Conference 2020	7-9 Feb 2020	University of Edinburgh	Glasgow
GeoTherm 2020	5-6 March 2020	European Geothermal Energy Council	Offenburg, Germany
GeoSciences PGR Conference	23-24 April 2020	University of Edinburgh	Edinburgh
7th Int. Meeting on Heat Flow	12-14 May 2020	GFZ	Potsdam, Germany
World Geothermal Congress 2020	24-30 April 2020	International Geothermal Association	Reykjavik, Iceland
GeoTherm 2021	March 2021	European Geothermal Energy Council	Offenburg, Germany
GeoSciences PGR Conference	April 2021	University of Edinburgh	Edinburgh
IMWA Conference 2021	June/July 2021	International Mine Water Association	Cardiff, Wales, UK
EGU 2022	April 2022	European Geosciences Union	Vienna, Austria

Table 8.2: Conferences of interest

8.4 Resources available

Source name	Total amount (£)	Comment
RTSG	3,450	NERC Research Training Support Grant
CASE funding	3,000	Coal Authority
Travel Grant	500	Estimated (application necessary)
TOTAL	7,000	Estimated

Table 8.3: Sources of income (total for 3 years)

8.5 Resources needed

Expenditure source	Amount (£)	Comment
Software license	540	Tecplot
Visit Mining Museum	11.50	Museum + Guided visit
COAL Authority visits	74.40	Reimbursed drom CASE funding
UK 7th Geothermal Synopsium	150.59	TRansport + Conference
Coming conferences:	Estimates:	
WGC	380 + 200	
GeoTHERM	50 + 250	Conference fees +
GradSchool Conference	175 x 2	Transport
IMWA	250 + 100	
EGU	350 + 200	
SUB-TOTAL	3,000	
Open-source licences	1,500	Estimations for 3 publications
Computing capacity / storage / software /	1,500	Reserves
TOTAL	7,000	Include all income sources

Table 8.4: Resources required and potential expenses (NB: The total expenses ignore the expenses types, which might or might not be covered by all income sources. More detailed budget analysis is required to define which expense could be covered by which income source).

9 Ethical and Health and safety considerations

- Data management, storage and diffusion: access to data from the Coal Authority requires the definition of a license agreement (to be done during CASE placement in January).
- No fieldwork planned
- Visit of mines organized by external organizations (Coal Authority, University of Newcastle, David Banks. . .)

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