phD Plan

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

Mylene Receveur

Christopher McDermott, Stuart Gilfillan, Andrew Fraser-Harris

phD in Geology

School of Geosciences
University of Edinburgh, Scotland
December 2, 2019

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 allowing water to be extracted at high rates. Mine-water constitute a low carbon heat source from which heat can be extracted using open-loop ground source heat pump systems.

[Knowledge gap] However, a few 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 temperature of the mine water (Gillespie et al., 2013). Additional factors to the regional geothermal gradient might therefore contribute to defining the temperature of mine water, which might also be impacted by the complexity of the interconnections between mine workings.

[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. Using mine-water as a heat energy source would therefore contribute to the 2025 UK target to decarbonize residential heat, by replacing gas boilers by low-carbon heating systems in all new homes (*Clean Growth - Transforming Heating* 2018). This would also participate to the net-zero emissions target recommended by the Committee on Climate Change to the UK Government, aiming to reduce greenhouse gas emission by 100% by 2050 in the UK and by 2045 in Scotland (Stark, 2019).

In addition to provide low-carbon energy, mine-water based heat systems represent cost-effective geothermal systems. Using mine-water as a source of energy indeed gives the opportunity to decrease costs associated the 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 and guide the licensing of heat (Ian Watson, Coal Authority, Pers. Com. 2019).

However, a few 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 that indicates that other factors than the geothermal gradient might contribute to define the temperature of mine water.

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, including the relative contributions of different heat sources and heat the transfer mechanisms. This will be used to assess the heat recovery potential and this the sustainability and heat storage capacity of mine reservoirs.The research project includes three main objectives.

The first objective is to create hydro-geological conceptual model(s) of flooded coal mines reservoirs to identify what are the main controls on the steady-state temperature in mines. This conceptual model will consider the relative contribution of different heat sources and the dominant heat transfer mechanisms, with the aim to get a better understanding of the temperature distribution within mines.

The second objective is to develop a numerical tool able to predict the steady state mine-water temperature as well as the changes in the production temperature with time as a result of heat extraction from GSHP systems. This tool will be used to predict the extent of the area impacted by heat mining around the production well, as well as the rate of energy recovery once extraction is stopped.

Finally, the third objective will be to determine the energy input necessary to create a sustainable heat reservoir in flooded coal mines.

2.3 Take home message

Flooded coal mines represent a great interest as low carbon heat energy resource. However, the sustainable use of heat from coal mines can only be achieved with an appropriate dimensioning of GSHP systems, which only depends on the good understanding of the heat capacity and recharge mechanisms of the underground. This represents a challenge in mines, where the presence of large interconnected mine voids tends to create complex hydrologic systems, difficult to solve numerically.

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 would be used to guide the licensing of heat with a scientific approach, but also support the the design of mine-water based heat extraction scheme, the assessment of sustainable production rate and the rate of heat recovery.

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 then 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, solar input, local heat sources as well as local/regional groundwater flow and convective flow in highly connected subsurface void on the mine temperatures. 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 assessing 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 distinctively data from naturally gravity-driven discharge areas and and from pumped water. While water naturally discharging on the surface might be representative of the steady-state conditions in the mine, pumping implemented to maintain water level below the ground surface might indeed induce turbulent flow and mixing, disturbing the natural temperature conditions.

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.
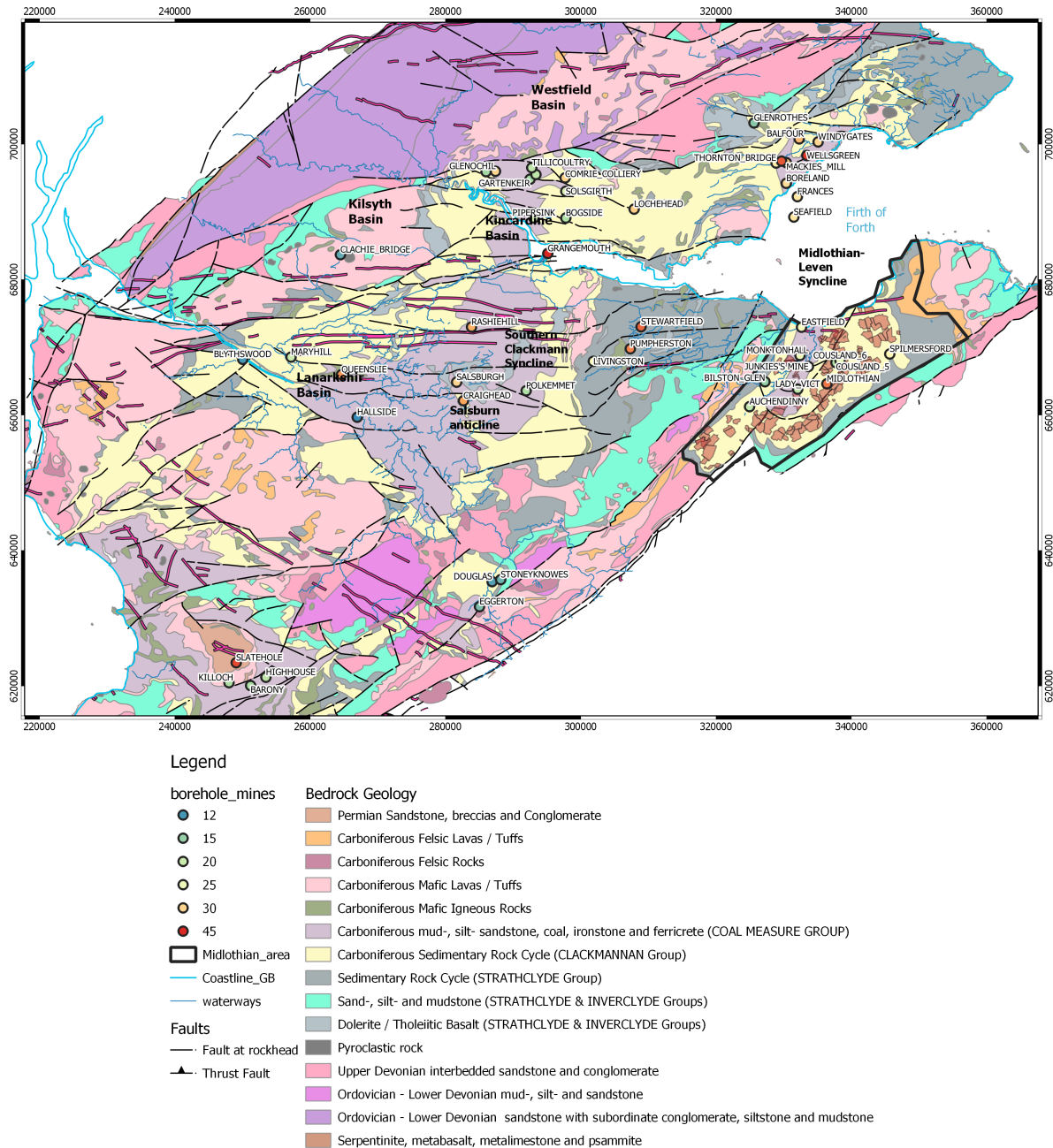

Figure 3.1: Geological map of the Midland Valley of Scotland

3.3   Data sources

Several factors need to be considered to understand the temperature distribution in mines. This includes the natural heat flow, solar influx, the presence of local heat generation (i.e. radioactive day, pyrite oxidation), 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 data can also be obtained from 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 directly linked to the geothermal potential evaluation of mine workings below Glasgow.

Additional data to be potentially collected include long-term temperature and geochemical data at several pumping/discharge points within the selected case study. In addition, micro-gravity or resistivity surveys might help identifying the presence of heterogeneities in the reservoir or density contrasts associated to the presence of i.e. granite intrusions, that represent potential source of local heat production.

3.4   Data analysis

GIS tools (i.e. QGIS) will first be used to analysis the spatial distribution of the data and perform cross analysis.

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) have been analyzed by Gillespie et al., 2013. Temperatures measured from nine boreholes in the Midland Valley range from 12 to 21°C, with a mean and 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 mine waters generally increases with depth according to the geothermal gradient, no correlation has been found between the depth of the measurements and the observed water temperature in the Midland Valley. In autumn 2008, new groundwater samples were collected as part of the Scotland Baseline Project, from boreholes abstracting water from Carboniferous sedimentary aquifers across the Midland Valley. Four of them originate from abandoned flooded mine workings (i.e. 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 Midland Valley. 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. In addition, recent studies reported average mine water temperatures of 11.5-13.3 °C and 14-15 °C for the Crynant, Dulais Valley, South Wales Coalfield (Farr et al., 2016) and the Caphouse Colliery (Burnside et al., 2016), 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, with no apparent geothermal potential

- 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 transfer mechanisms controlling the temperature distribution in mines?

4.1.4 Hypothesis

- H0: The steady state temperature in mines mostly depends on the local geothermal gradient (conductive heat transfers in porous medium) and the extent of gravity-driven mixing in open voids

- H1: The rate of temperature change of the extracted water mainly depends on the hydraulic conductivity of the mine voids, on the number of un-mined low conductivity coal seams, on the production rate and the distance from coal infiltration/recharge zones.

- H2: The recovery rate is mainly influenced by the thermal properties of the rock, the presence of local heat sources 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 changes in fluid chemistry, the monitoring site location, the geological structure and volume of surrounding rock types, the historic rock temperature measurements and the flooding/dewatering history of the mine to identify the potential contributions from hydrological structures on the discharged/pumped temperature as well as the possible sources of heat. This will be done 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).
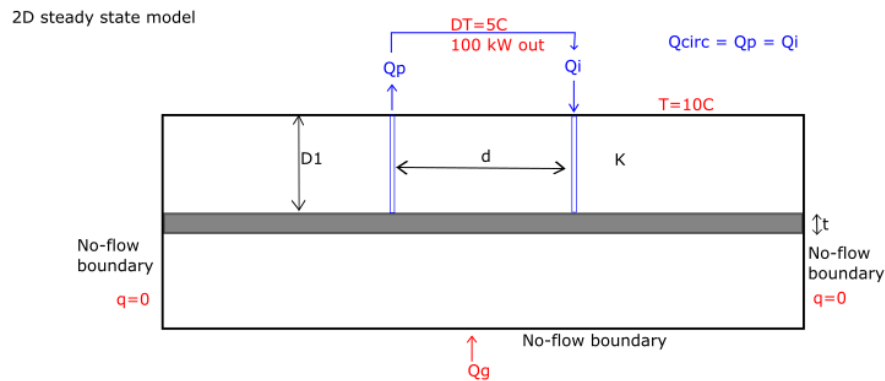

Figure 4.1: Simplified 2D Conceptual model of a mine gallery (longwall panel)

- Using 2D numerical models, perform a sensitivity analysis to evaluate the relative impact on pumped/discharged water temperature 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), 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 and chemical composition and its 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 (i.e. Fig. 4.2)

- Analysis of the most sensitive geometrical, technical or numerical parameters relative to the mine-water temperature and assessment of typical values for modeling input valable for other case studies.

- 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)
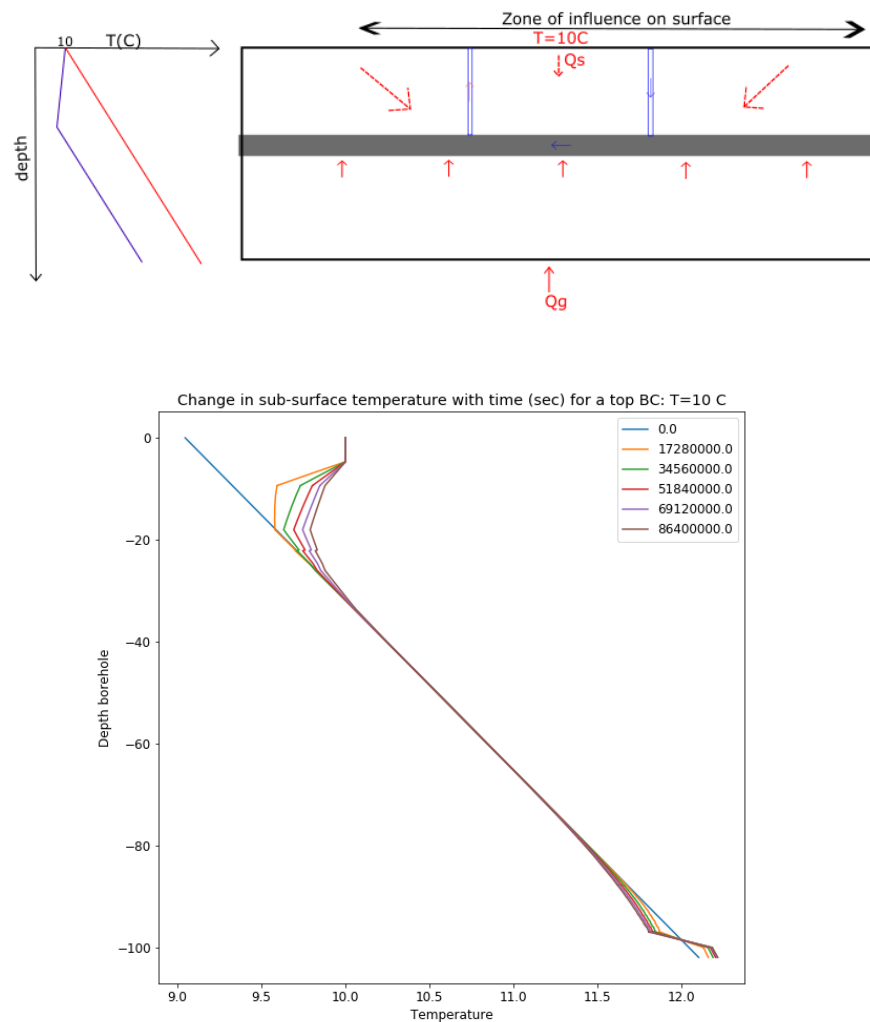

Figure 4.2: Example of steady state temperature results obtained from the conceptual approach 1

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 heat depletion rate might be higher.

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 field by collapsed roof material and the former shafts 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, solution transport 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 approaches 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). While analytical models solve for the exact mathematical solutions of flow and heat transport by considering homogenous systems, and therefore require geometrical simplifications (Banks et al., 2009; Loredo et al., 2017), numerical models allow creating more realistic representations of mining scenarios. However, such models might be subjected to numerical instabilities and generally require more data and computational time, which make them more complex to use and might limit 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 or numerical models (Ghoreishi-Madiseh et al., 2012)

- The mined areas or goaf (i.e. 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

What are the disturbances caused by the extraction of heat from mines? Can we predict the temperature change?

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

4.2.5   Methods

- Develop 3D numerical model of two different study areas, based on detailed 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 flooding, simulate the temperature change due to production for different production scenarios.

- Simulate the heat recovery time after the cessation of heat extraction/injection

4.2.6 Output

- 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

- 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

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 mainly depends on the available water volume in the flooded mine voids V (m3) and on the mine-water temperature distribution. The potential available heat energy E (W) that can be extracted from mine water will in addition depends on the water abstraction rate Q (m3/s), 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 (Ehp) can can be calculated as the product of the mean pumping rates Q by the temperature change across the heat exchanger, and 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 estimated of extractable energy rate from water using heat pump (Ehp) and captured energy rate (Ec) to assess the geothermal potential (J) of the Gaspe Mine, Canada. The energy rate that can be captured by the pumping well was estimated by multiplying the area affected by pumping well, determined from multiple drawdown simulation predictions, by the heat ux. The sustainable energy production rate was here assumed to represent the pumping rate at which the captured energy rate Ec is half the rate of energy extraction from water by heat pumps Ehp.

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. Chaptter 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: 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. geobattery).

4.3.6   Outputs

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

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 variations, have an influence on the pattern of the shallow subsurface temperature profile.

4.4.2   Knowledge gap

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

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 mean surface heat flux of XXX J/s with variations of +/- XXX J/s is required annually to reproduce the shallow sub-surface 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 XXX J/s and XXX J/s of surface heat flux are necessary annually 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's computers will allow ensuring a safe version control of the different phD research documents and script (see Tab. 5.1).

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
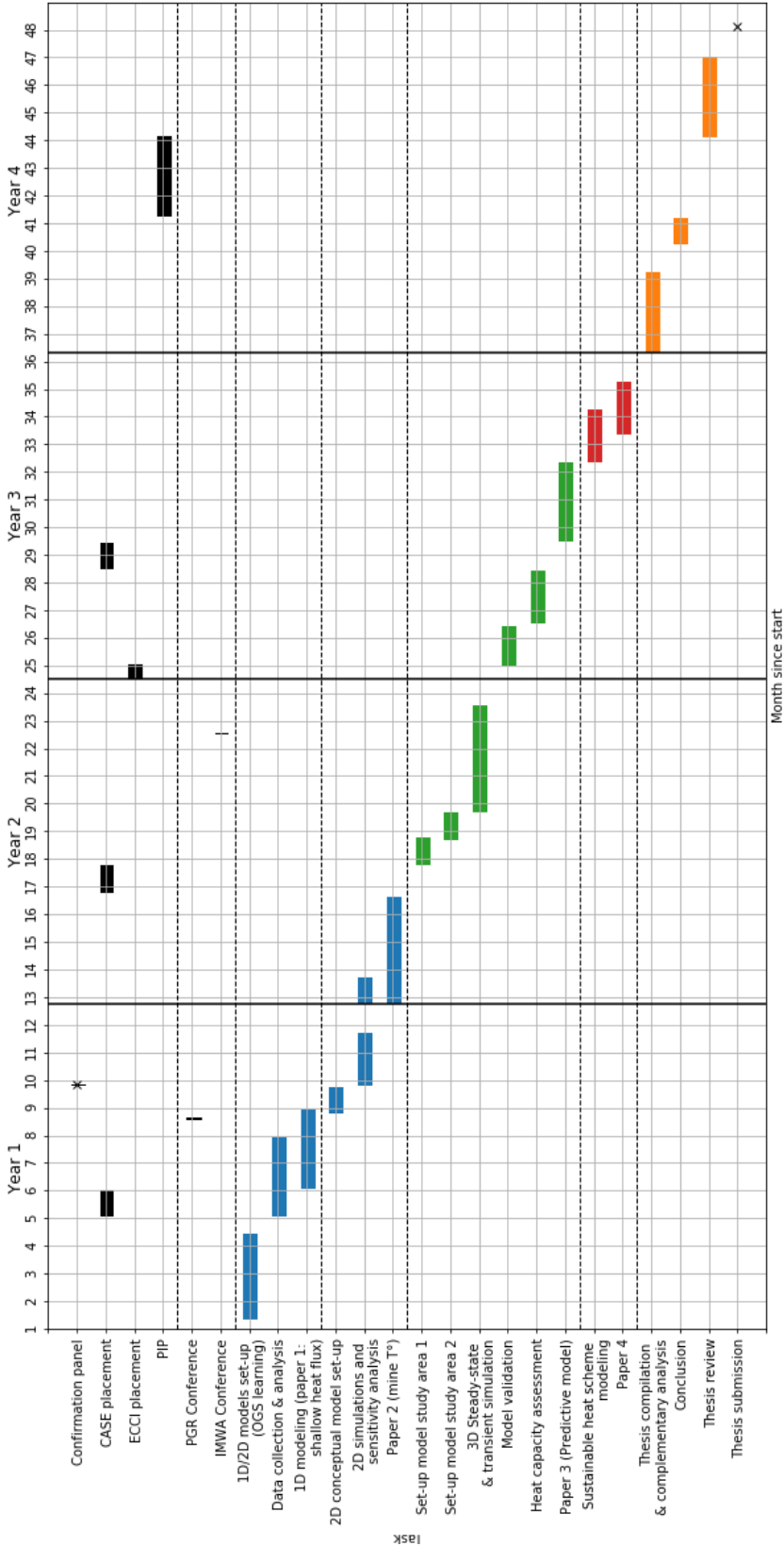
Figure 6.1: GANTT chart

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

8.5   Resources needed

Expenditure source	Amount	Comment
Software license	£540	TecPlot
Visit Mining Museum	£11.50	Museum + guided visit
Conferences attended: UK 7th Geothermal symposium	£150.59	
Coming Conferences		Estimation for conference fees, transport (flight, train or car) and additional fees (i.e. food, accommodation)
- WGC		
- Conference fee	£380	
- Transport	£200	
- GeoTHERM		
- Conference fee	£50	
- Transport	£250	
- PGR Conf	£175 x 2	
- IMWA		
- Conference fee	£250	
- Transport	£100	
- EGU		
- Conference fee	£350	
- Transport	£200	
TOTAL	~£3,000	
Open-source Licenses	~£1,500	Estimate for 3 publications
Computing capacity / software	~£1,500	Reserves
COAL Authority visit	£74.40	Reimbursed from CASE funding
Total	~£7,000	Include all income sources

Figure 8.1: Resources required and potential expenses. The total expenses does consider the type of expense, which might not be covered by all income sources

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. . .)

References

Adams, R. and Younger, P. (Mar. 2001). A Strategy For Modeling Ground Water Rebound In Abandoned Deep Mine Systems. *Ground Water* [online]. 39.2, pp. 249–261. ISSN: 0017-467X, 1745-6584. DOI: 10.1111/j.1745-6584.2001.tb02306.x. Available from: `http://doi.wiley.com/10.1111/j.1745-6584.2001.tb02306.x` [Accessed Nov. 26, 2019].

Andrés, C., Ordóñez, A., and Álvarez, R. (Mar. 2017). Hydraulic and Thermal Modelling of an Underground Mining Reservoir. *Mine Water and the Environment* [online]. 36.1, pp. 24–33. ISSN: 1025-9112, 1616-1068. DOI: 10.1007/s10230-015-0365-1. Available from: `http://link.springer.com/10.1007/s10230-015-0365-1` [Accessed Oct. 31, 2019].

Athresh, A. P., Al-Habaibeh, A., and Parker, K. (Aug. 2015). Innovative Approach for Heating of Buildings Using Water from a Flooded Coal Mine Through an Open Loop Based Single Shaft GSHP System. *Energy Procedia* [online]. 75, pp. 1221–1228. ISSN: 18766102. DOI: 10.1016/j.egypro.2015.07.162. Available from: `https://linkinghub.elsevier.com/retrieve/pii/S1876610215009303` [Accessed Oct. 31, 2019].

Banks, D., Fraga Pumar, A., and Watson, I. (Aug. 1, 2009). The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology* [online]. 42.3, pp. 347–357. ISSN: 1470-9236, 2041-4803, 1470-9236. DOI: 10.1144/1470-9236/08-081. Available from: `http://qjegh.lyellcollection.org/lookup/doi/10.1144/1470-9236/08-081` [Accessed Oct. 31, 2019].

Banks, D. (2016). "Making the Red One Green â" Renewable Heat from Abandoned Flooded Mines". In: 36th Annual Groundwater Conference of the International Association of Hydrogeologists: "Sustaining Ireland's Water Future: The Role of Groundwater". Tullamore, County Offaly, Ireland, pp. 1–9.

Banks, D., Athresh, A., Al-Habaibeh, A., and Burnside, N. (Mar. 2019). Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. *Sustainable Water Resources Management* [online]. 5.1, pp. 29–50. ISSN: 2363-5037, 2363-5045. DOI: 10.1007/s40899-017-0094-7. Available from: `http://link.springer.com/10.1007/s40899-017-0094-7` [Accessed Nov. 26, 2019].

Banks, D., Skarphagen, H., Wiltshire, R., and Jessop, C. (2004). Heat pumps as a tool for energy recovery from mining wastes. *Geological Society, London, Special Publications* [online]. 236.1, pp. 499–513. ISSN: 0305-8719, 2041-4927. DOI: 10.1144/GSL.SP.2004.236.01.27. Available from: `http://sp.lyellcollection.org/lookup/doi/10.1144/GSL.SP.2004.236.01.27` [Accessed Nov. 26, 2019].

Banks, D., Younger, P. L., Arnesen, R.-T., Iversen, E. R., and Banks, S. B. (Oct. 17, 1997). Mine-water chemistry: the good, the bad and the ugly. *Environmental Geology* [online]. 32.3, pp. 157–174. ISSN: 0943-0105, 1432-0495. DOI: 10.1007/s002540050204. Available from: `http://link.springer.com/10.1007/s002540050204` [Accessed Nov. 26, 2019].

Brouyere, S., Orban, P., Wildemeersch, S., Couturier, J., Gardin, N., and Dassargues, A. (June 2009). The Hybrid
 Finite Element Mixing Cell Method: A New Flexible Method for Modelling Mine Ground Water Problems.
 Mine Water and the Environment [online]. 28.2, pp. 102–114. ISSN: 1025-9112, 1616-1068. DOI: 10.1007/
 s10230-009-0069-5. Available from: http://link.springer.com/10.1007/s10230-009-0069-5
 [Accessed Nov. 26, 2019].

Burley, A., Edmunds M., W., and Gale, I. (1984). *Catalogue of geothermal data for the land area of the United
 Kingdom*. Second revision. British Geological Survey.

Burnside, N., Banks, D., and Boyce, A. (July 2016). Sustainability of thermal energy production at the flooded
 mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. *International Journal of Coal
 Geology* [online]. 164, pp. 85–91. ISSN: 01665162. DOI: 10.1016/j.coal.2016.03.006. Available from:
 https://linkinghub.elsevier.com/retrieve/pii/S0166516216300489 [Accessed Oct. 31, 2019].

Clean Growth - Transforming Heating (2018). Department for Business, Energy and Industrial Strategy, p. 136.

Farr, G., Sadasivam, S., Manju, Watson, I., Thomas, H., and Tucker, D. (July 2016). Low enthalpy heat recovery
 potential from coal mine discharges in the South Wales Coalfield. *International Journal of Coal Geology*
 [online]. 164, pp. 92–103. ISSN: 01665162. DOI: 10.1016/j.coal.2016.05.008. Available from: https:
 //linkinghub.elsevier.com/retrieve/pii/S0166516216302002 [Accessed Oct. 31, 2019].

Ferket, H., Laenen, B., and Van Tongeren, P. (2011). "Transforming ï‚ooded coal mines to large-scale geother-
 mal and heat storage reservoirs: what can we expect?" In: *Mine water - Managing the Challenges*. IMWA
 Congress 2011. Aachen, Germany, pp. 171–175.

Ghoreishi-Madiseh, S. A., Ghomshei, M. M., Hassani, F. P., and Abbasy, F. (2012). Sustainable heat extraction
 from abandoned mine tunnels: A numerical model. *J. Renewable Sustainable Energy*, p. 17.

Ghoreishi-Madiseh, S., Hassani, F., and Abbasy, F. (Nov. 2015). Numerical and experimental study of geothermal
 heat extraction from backfilled mine stopes. *Applied Thermal Engineering* [online]. 90, pp. 1119–1130. ISSN:
 13594311. DOI: 10.1016/j.applthermaleng.2014.11.023. Available from: https://linkinghub.
 elsevier.com/retrieve/pii/S1359431114010217 [Accessed Oct. 31, 2019].

Gillespie, M., Crane, E., and Barron, H. (2013). *Study into the Potential for Deep Geothermal Energy in Scotland
 - Volume 2*. AEC/001/11. Scottish Government, p. 129.

Guo, P., Zheng, L., Sun, X., He, M., Wang, Y., and Shang, J. (2018). Sustainability evaluation model of geother-
 mal resources in abandoned coal mine. *Applied Thermal Engineering* [online]. 144, pp. 804–811. ISSN:
 13594311. DOI: 10.1016/j.applthermaleng.2018.06.070. Available from: https://linkinghub.
 elsevier.com/retrieve/pii/S1359431117364888 [Accessed Oct. 31, 2019].

Hall, A., Scott, J. A., and Shang, H. (Feb. 2011). Geothermal energy recovery from underground mines. *Renew-
 able and Sustainable Energy Reviews* [online]. 15.2, pp. 916–924. ISSN: 13640321. DOI: 10.1016/j.rser.
 2010.11.007.

Hamm, V. and Bazargan Sabet, B. (2010). Modelling of fluid flow and heat transfer to assess the geothermal
 potential of a flooded coal mine in Lorraine, France. *Geothermics* [online]. 39, pp. 177–186. DOI: 10.1016/
 j.geothermics.2010.03.004.

Kolditz, O., Bauer, S., Bilke, L., Böttcher, N., Delfs, J. O., Fischer, T., Görke, U. J., Kalbacher, T., Kosakowski,
 G., McDermott, C. I., Park, C. H., Radu, F., Rink, K., Shao, H., Shao, H. B., Sun, F., Sun, Y. Y., Singh, A. K.,

Taron, J., Walther, M., Wang, W., Watanabe, N., Wu, Y., Xie, M., Xu, W., and Zehner, B. (Sept. 2012). Open-GeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. *Environmental Earth Sciences* [online]. 67.2, pp. 589–599. ISSN: 1866-6280, 1866-6299. DOI: `10.1007/s12665-012-1546-x`. Available from: `http://link.springer.com/10.1007/s12665-012-1546-x` [Accessed Oct. 31, 2019].

Luo, J. (2014). "Experimental measurements and numerical modeling of a Ground Source Heat Pump system". PhD thesis.

Małolepszy, Z. (2003). "Low Temperature, Man-Made Geothermal Reservoirs in Abandoned Workings of Underground Mines". In: Stanford Geothermal Workshop. Standford.

Malolepszy, Z., Demollin-Schneiders, E., and Bowers, D. (2005). "Potential Use of Geothermal Mine Waters in Europe". In: World Geothermal Congress 2005. Antalya, Turkey.

Ordonez, A., Jardon, S., Alvarez, R., Andresa, C., and Pendasa, F. (2012). Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. *Journal of Environmental Monitoring* [online]. 14.8, p. 2127. ISSN: 1464-0325, 1464-0333. DOI: `10.1039/c2em11036a`. Available from: `http://xlink.rsc.org/?DOI=c2em11036a` [Accessed Nov. 26, 2019].

Raymond, J. and Therrien, R. (Apr. 2008). Low-temperature geothermal potential of the flooded Gaspé Mines, Québec, Canada. *Geothermics* [online]. 37.2, pp. 189–210. ISSN: 03756505. DOI: `10.1016/j.geothermics.2007.10.001`. Available from: `https://linkinghub.elsevier.com/retrieve/pii/S0375650507000818` [Accessed Oct. 4, 2019].

Renz, A., Rühaak, W., Schätzl, P., and Diersch, H.-J. G. (Mar. 2009). Numerical Modeling of Geothermal Use of Mine Water: Challenges and Examples. *Mine Water and the Environment* [online]. 28.1, pp. 2–14. ISSN: 1025-9112, 1616-1068. DOI: `10.1007/s10230-008-0063-3`. Available from: `http://link.springer.com/10.1007/s10230-008-0063-3` [Accessed Oct. 31, 2019].

Robins, N. (1990). *Hydrogeology of Scotland. Hydrogeology of Scotland.* British Geological Survey. London. ISBN: 0 11 884468 7.

Rodríguez, R. and Díaz, M. B. (July 2009). Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. *Renewable Energy* [online]. 34.7, pp. 1716–1725. ISSN: 09601481. DOI: `10.1016/j.renene.2008.12.036`. Available from: `https://linkinghub.elsevier.com/retrieve/pii/S096014810900007X` [Accessed Oct. 31, 2019].

Stark, C. (2019). *Net Zero: The UK's contribution to stopping global warming*. Committee on Climate Change, p. 277.

Wolkersdorfer, C. (2008). *Water Management at Abandoned Flooded Underground Mines*. 465 pp. ISBN: 978-3-540-77330-6. Available from: `http://www.springer.com/dal/home/geosciences/hydrogeology?SGWID=1-40515-22-173789307-0`.

Younger, P. (2001). Mine water pollution in Scotland: nature, extent and preventative strategies. 265, pp. 309–326.

Younger, P. L. (2004). Making water: the hydrogeological adventures of Britain in early mining engineers. *Geological Society, London, Special Publications* [online]. 225.1, pp. 121–157. ISSN: 0305-8719, 2041-4927. DOI: `10.1144/GSL.SP.2004.225.01.09`.