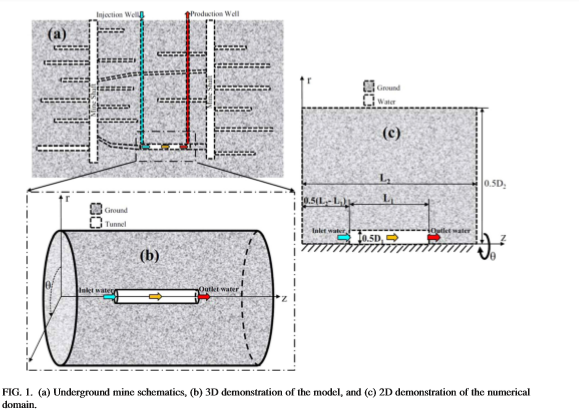
### Heat transfer in mine tunnels, Ghoreishi Madeish et al. (2012)

Ghoreishi Madeish et al. (2012) used a Finite Volume Modelling approach to evaluate the sustainable heat extraction from abandoned mine tunnel and address the issues of thermal breakthrough (Loredo et al., 2017). A tunnel of simple geometry (characterized by its length and cross section) embodies the bulk geometry of the model. In the numerical model, they assume that the water infiltration through the rock mass into the tunnel negligible compared to flow within mine gallery and that the natural convection inside the rock mass negligible in comparison to the forced convective flow inside the tunnel. As no regional hydrological gradient is assumed after the mine is fully flooded, the water movement inside the rock mass is considered not-significant (only the gradient induced by production is considered). Therefore, the only component of the flow field is the velocity of water inside and along the tunnel. Two heat transfer mechanisms are considered: forced convection inside the tunnel and conduction in the rock mass. There, the thermal properties of water are used to solve the equation of unsteady convective heat transfer in the tunnel (with w the longitudinal component of water velocity) and the thermal properties of the rock mass are used to solved for equations of unsteady heat conduction in the ground (w=0). The value of thermal conductivity is calculated at each point following the “harmonic mean method” (Patankar) so that the heat flux exchanged between the water and the ground regions is balanced. As initial condition, the rock mass and the underground water are set at an equilibrium temperature Tg. Isothermal condition is assumed for all boundaries except for r = 0 axis (adiabatic BC) and an injection temperature Tin is set at the tunnel inlet. As the temperature of water/rock mass around the tunnel inlet is lower than at the outlet, a longitudinal temperature gradient is formed, creating a conductive heat flux along the z-axis in the rock mass in addition to radial heat flux across the rock zone. During the simulation, aiming at predicting the resource reaction to different heat extraction scenarios, seasonal heat load variations are modeled by adjusting pumping flow rate through the mine tunnel.

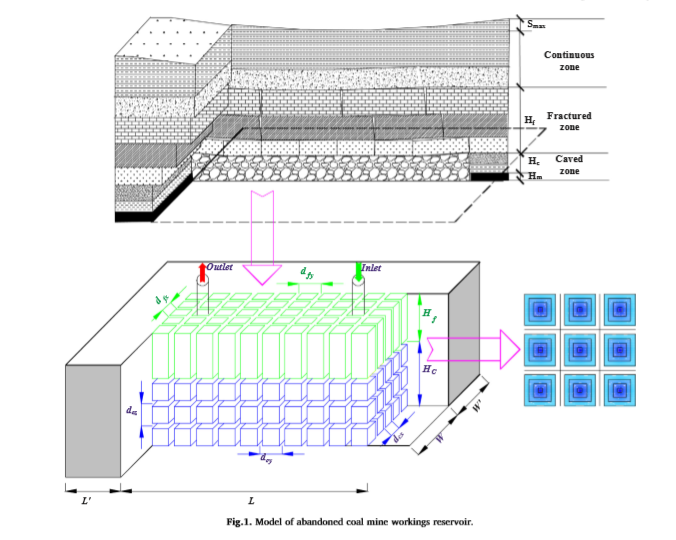


According to Ghoreishi Madeish et al. (2012), the most important parameters in modeling heat flow in mine tunnels are the thermal conductivity of the mine rocks (determine the sustainable rate of heat extraction from mines), and to a lower extent the permeability and specific heat capacity of the mine rocks. In the “mine tunnel” approach, the dimensions of the tunnel (length and cross section) impact the total recoverable heat from the mine, while the temperature of extraction depends on the rate of heat extraction from the resource. Ghoreishi Madeish et al. (2012) showed using a simple mine tunnel geometry (numerical modeling approach) that an area of up to 40 m around the tunnel is affected by heat extraction during the life time of the project. Results also show that seasonal heat extraction and seasonal use of cold/warm water from the mine allow heat recovery and is likely to better sustain the heat resource production in long term, increasing the system lifetime (Ghoreshi et al, 2012; Hall et al., 2011; Hamm and Bazargan Sabet, 2010). This procedure allows taking advantage of the storage capacity of the underground (Ruhaak and Renz, 2010).

### Dual-porosity medium (Guo at al., 2018)

Guo et al. (2018) also performed an evaluation of the potential and the sustainability of geothermal resources in abandoned coal mines using a numerical approach (MINC method of TOUGH2). In this model, the mine thermal reservoir (mined area) is considered as a dual-porosity medium, modelled as a typical working face formed of a caved zone and a fractured zone (the continuous zone situated on top of those and affected by elastic deformation is assumed to be an aquifuge not connected to the goaf). The caved zone, which contains the goaf material, is assumed to be isotropic while the overlying fracture zone, composed of regular vertical fractures, is anisotropic. For both zones, two types of porosity are taken into account: the primary porosity (small fractures and pores in the rock matrix), measured by experiments, and the secondary porosity (fractures induced by mining). The volume and spatial distribution of secondary fractures is calculated based on the volume of mined-out area, for different types of roof rock. The bulking factors, which represents the change in rock volume due to broken solid rock, were calculated for both the caved and fractured zones based on the height of each zone (estimated from the roof rock strength properties and the thickness of the mined seam) and on mining parameters (i.e. volume of mining coal and subsidence of the fractured zone). The exponential decrease in the bulking factor in the fractured zone with height (due to change in fracture permeability) was taken into account for the estimation of the average total bulking factor, used to calculate the total secondary porosity produced by mining. In the model, the main reservoir (caved and fracture zones) is surrounded by large a large continuous media aiming to minimize the influence of boundary conditions. Temperature equilibrium is assumed between the fluid and the rock mass as initial condition. During the simulation, injection and extraction of water is performed at both ends of the working face, and flow and heat transfer in the fractures of the mined-out area are calculated to analyze the effects of injected temperature, flow rate and lifetime on the thermal storage capacity and sustainability of the mine heat reservoir.

Guo et al. (2018) showed that the geothermal potential of flooded mine depends more on the height of the fracture zone than on the fracture permeability and that an increasing roof strength tends to increase the sustainability of heat production. Strong roof rock strength tends to produce wider/more sparse fracture distributions, influencing the temperature distribution and increasing the heat production. While the permeability of the roof is beneficial to heat transfer (production temperature increases with roof permeability), the fracture permeability of the fractured zone (volume/aperture) tends to decrease the production temperature. In addition, the heat extraction rate is closely related to the injection temperature and lifetime of the production. The rate of temperature drop is quicker for high flow rate and lower injection temperature, but tends to decrease with time.



### Combined 3D porous medium and 1D pipe flow (Raymond and Therrien, 2008)

Raymond and Therrien (2008) estimated the energy attainable from mine water and the geothermal potential of the ﬂooded Gaspe Mines in Quebec (Canada). Groundwater flow in the mine was simulated using the 3D finite element simulator HydroGeoSphere (Therrien et al., 2004), able to solve simultaneously for 1D pipe flow and 3D porous media flow. The 3D domain was indeed here divided in two distinct media. First, the underground roads and shafts were represented as network of 1D line elements along which pipe flow was computed. The nodal flow term for these elements was either transferred to the flow equations associated to the 3D porous medium using a fluid transfer term (Adams and Younger, 2001) or directly added to the nodal flow terms of the 3D elements of the porous medium (Boyaud and Therrien, 2004). Second, the workings were represented as a 3D sub-domain of high hydraulic conductivity relative to host rock, and geometrically constrained by maps of excavated zones and their relative elevations. Due to the lake of detailed records of the current workings state (i.e. collapse, filled workings…), hHomogeneous and isotropic values for the hydraulic conductivity, porosity and speciﬁc storage coefﬁcient were used for each sub-domain.

A 3D mesh composed of 123,000 nodes was generated by stacking 40 layers of 2D triangular elements along the vertical axis. The bottom boundary was set deep enough to minimize its influence on groundwater flow and to be considered as impermeable. Topographic highs were set as recharge areas (Dirichlet boundary conditions, constant hydraulic head), while nodes at the surface in streams/valleys were assigned a constant head equal to the surface elevation. A positive water flux representing recharge due to precipitation was assigned to the surface nodes. No flow boundaries were set on the lateral extremities of the model.

The model was first calibrated from alternated/repeated transient pumping test and steady-state groundwater ﬂow simulations. The hydraulic properties for the host rock and underground workings (hydraulic conductivities and speciﬁc storage coefﬁcients) were adjusted so that simulated drawdown reproduces the hydraulic response of the Gaspe Mines to the pumping test, considering a constant pumping rate and no infiltration at the surface. The first-type boundary conditions at topographic highs (inﬁltration ﬂux) were adjusted so that modelled drawdown match measured water table elevation before the pumping test (natural steady-state flow conditions). Calibration resulted in values for the hydraulic head before pumping and infiltration flux. Multiple simulations at various pumping rates were then used to determine area affected by pumping well (transient ﬂow conditions with no infiltration flux specified at the surface). This affected area resulting from the model drawdown predictions was multiplied by the heat ﬂux to estimate the energy rate that can be captured by the pumping well, which was compared to extractable energy rate. An energy balance calculation was used to estimate the geothermal potential / resource Et (J) of the mine. This approach assumes that the drawdown caused by pumping approaches steady state after a heating season and that the heat recharge to pumped water is due to the geothermal heat flux (i.e. captured energy rate), advection from inflowing groundwater, and conduction when the system starts cooling. If conduction and advection are neglected and considering that energy extraction occur only half time of the year relative to a constant heat flux, then the sustainable energy production rate corresponds to the pumping rate at which the captured energy rate is half the rate of energy extraction from water by heat pumps :

With Ec (W) the captured energy rate, Ehp (W) the extractable energy rate from water using heat pump.

### Combined 3D/2D/1D model of porous medium and pipe flow (Renze et al., 2009)

In their study, Renze et al. (2009) used different flow equations, including the Darcy (laminar flow, e.g. Diersch, 2005), Hagen–Poiseuille (slow-moving laminar pipe flow), and Manning–Strickler (Manning’s equation for 1D pipe/channel turbulent flow, e.g. Diersch, 2005) equations to simulate fluid flow within 2D triangular finite element mesh using the FEFLOW code. A resolution of 3 to 14 m was used to simulate Darcy flow within the rock mass, and laminar and turbulent flow in the mining structures were calculated by adding 1D elements. Renz et al. (2009) indeed suggested that shafts or tunnels may be considered as 1D and coal seams as 2D, simplifying the applications of empirical flow equations for turbulent fluid flow. This simplification might however not be suitable in cases where high Rayleigh numbers allow heat transport in the system though convection, only feasible in 3D. The 2D model was based on a geological cross-section with specific rock properties. Elements representing the mining voids were divided into four types: shafts (open and with a cross sectional area of 20m²), roadways (considered as tunnels with a cross sectional area of 25 m², connecting different parts of the mine in the horizontal direction), driving and caverns, considered as a porous medium of very high hydraulic conductivity. While turbulent flow is expected in large mine voids (roadways and shafts) with high velocities and high pressure losses, laminar flow is expected in backfilled part of goaf materials, drivings and caverns, that represent the largest voids in the mines (roof elevations of 5 and 10 m, respectively) and thus contain the major portion of the mine water. As the extent of those are mainly horizontal (i.e. orthogonal to the plan of the 2D model), the real behavior of heat and mass flow in these voids cannot be reliably simulated. Their ability to store large amount of water (i.e. thermal energy) was therefore represented by a heat capacity equivalent to the complete depth, applied to the 1D elements. Initial conditions were calculated from the boundary conditions in a steady-state simulation without injection and extraction of mine water.

In the density-dependent simulation, results showed that movement due to free convection were negligible, showing insignificant density effects. In the heat extraction/injection simulation, cold water was injected at the bottom of the shaft at a constant temperature of 3°C and a flow rate of 120 m3/day. Results show that the Strickler coefficients (roughness coefficient that determine the pressure loss due to friction between the fluid and channel walls in the Manning-Strickler equation) have little influence on the modelled temperature evolution. A 3D model was then set up using a 3D porous media approach to get volumetric information on the heat transfer resulting from geothermal operation. The mesh was composed of 600000 nodes of prismatic elements.

The table below summarized the BC used for the 2D and 3D models.

|  |  |  |
| --- | --- | --- |
|  | 2D | 3D |
| TOP BC | Impermeable boundaries  fixed T°= 10°C | Head = river level  Recharge = 90 mm/s  fixed T°= 10°C |
| BOTTOM BC | Impermeable boundaries  constant geothermal flux | Impermeable boundaries  constant geothermal flux |
| LATERAL BC | Impermeable boundaries | Impermeable boundaries |
| EXTRACTION /  INJECTION POINTS | hydraulic head h = 0 m | -extraction at the bottom of the deepest shaft  -injection: constant T°=3°C at the bottom of the model |
| HYDRAULIC CONDUCTIVITY   * Shafts / caverns * Drivings/ roadways |  | n = 1  K = 5 m/s  c = 4.2 x 106 J/m3.K  k = 0.65 W/m.K |

Renz et al. (2019) compared the classic Darcy flow modelling approach to the 1D/2D model. They showed that for conductivity contrast between the mine void and the rock <10 5 m/s, the higher the mine void conductivity, the smaller the decrease in extraction temperature. Above contrasts of 10 5 m/s, the greater the mine voids hydraulic conductivity and the greater/quicker is the decrease in extraction temperature. For low K, the cold water mainly flows within the lowermost galleries and is separated from the warm water above due to density effects. From K=104 m/s, mixing of warm and cold water occur as a result of the establishment of free convection within the mine voids, leading to faster transport of cold water toward the extraction well **(layering of cold/warm water is therefore only possible for a certain range of hydraulic conductivity values)**. The major benefit of the porous medium approach is therefore that it takes into account the effects of free convection. However, the overall heat storage from large mining voids are not properly accounted for as in the 1D/2D model.

### Modeling of French mines - Hamm and Bazargan Sabet (2010)

Hamm and Bazargan Sabet (2010) used a numerical modeling of fluid flow and heat transfer to assess the geothermal potential of a flooded coal mine in Lorraine (France). The models take into account the geometry of the mine working networks to determine precisely the thermal breakthrough, and validated by fitting in-situ flooding tests. In an initial model composed of ~1M tetrahedral elements was run to simulate free convection within the shaft induced by water density differences, to determine the resulting steady-state mixing temperature together with an estimate of a critical value of the fluid thermal Rayleigh number. The water in the reservoir and the surrounding rocks are assumed to be initially in thermal equilibrium. A constant geothermal gradient and a fixed temperature boundary between the shaft wall and the surrounding rocks are defined.

Results showed that free convection is the main heat transfer process in mine shafts through efficient intra-well mixing that fixe the temperature along the shaft close to the average of the temperatures at the top and bottom (in case where only one gallery is crossed at the bottom of the shaft). The presence of several galleries intersecting the shaft at different levels induces local water mixing and allows the establishment of a higher temperature at the bottom of the shaft.

Using the MARTHE software, the temperature evolution of the production zone over time was then calculated for different production/injection rates. A model of more than 1M hexahedral elements was used, representing a sub-set of three levels of galleries among 18 levels modelled from 193m to 1250m depth. Two regimes were considered in the mine voids:

* high-velocity in the network of highly conductive shafts/galleries (special porous media where porosity is such that the section open to flow is equal to the gallery/shaft cross-section)
* low-velocity in the less permeable porous rock mass (considering a **ratio between the gallery/shaft and rock permeabilities of 105**).

In this approach, it is assumed no direct hydraulic and thermal connection between the production zone and the upper galleries through the production shaft.

Hamm and Bazargan Sabet (2010) suggest that the assumption of equivalent porous media for mine workings is adequate when considering large-scale modelling. However, this approach can be improved by using a multi-layer model taking into account detailed digital maps of the mine’s galleries/shafts, better describing the 3D geometrical and hydraulic connections in the mines.

## Mine water stratification

According to Burnside et al. (2019), the heat flow in flooded mines is dominated by advection of heat. Water bodies tend to form density-related stratification resulting from the mixing of cold meteoric water and warmer saline water originating from depth (Nuttall and Younger, 2004).

Following long periods of abandonment, mine waters tend to become geochemically stratified, with better-quality water generally lying above poorer-quality ones (Wolkersdorfer, 2008; Nuttall & Younger, 2004). Geochemical stratification in the Heerlen mine, the Netherlands, suggested the infiltration of different water types at different depth during and after mining (Ferket et ak., 2011). There, electrical conductivity (EC) measurements were used as a useful marker for distinguishing between shallow and deeper sources.

Pumping water from mine generally encourage turbulent water mixing within the mine, which can destroy density-related stratification in wells and reduce the water quality (Burnside et al., 2019). The impact of this induced mixing dynamics in the Hope Shaft, Caphouse Colliery was studied by Burnside et al. (2019) using temperature, conductivity, pH, major ions and stable isotopes of O, H and S to understand the potential of the mine water body for sustainable heat generation. Results indicated no significant change in the water geochemistry during the study period, but the long-term chemical analysis from archive data revealed a general mine water quality recovery trend following the mine closure and the subsequent flooding. According to Hamm et al. (2010), temperature decrease due to forced convection is rather limited when water is pumped from the bottom of the shaft, and depends mainly on the pumping rate.

### Malolepszy (2015)

Malolepszy (2015) used two 2D TOUGH2 numerical models to simulate heat exchanges and temperature recovery of abandoned coal mine workings in the Nowa Ruda coal mine in Poland. With an average geothermal gradient of 32°C/km in Polish coal fields, temperatures of 30-50°C are expected at the deepest levels of the mines. Low-conductivity horizontal rock layers constitute cap rocks for the inflow of geothermal heat, potentially leading to thermal anomalies beneath thick layers of coal-bearing formations. In flooded mines, other local thermal anomalies might be due to mineral oxidation processes that tend to disturb the natural thermal regime of the mine (Jessop 1995). The first 2D model was built based on a vertical geological cross-section that preserved natural dips and thickness of the rock beds. This model was used to calculate natural-state conditions, simulate the conditions under mining activity (assuming a cooling of 8C) and the temperature recovery in the working after the stop of the mining activities. Results showed that the time required for temperature to return to natural thermal conditions in a rock massif where cooling has occurred is about 10 years. A second planar model, representing a 50m thick layer of rocks in the deeper part of the abandoned workings of the Piast mining field, was then used to simulate natural conditions, assuming terrestrial heat flow from the lowest part of the model. Scenarios of production /injection of mine water were then simulated with flow rates of 10 and 20 l/s. The model used a well doublet with a separation distance of 1.5 km, consisting of a producer well extracting 23C water at 660m depth and an injection well drilled down to 350 m and injecting water at 2-4°C. Results indicated a cooling by 4°C for 10 l/s and 10°C for 20 l/s.

### Andrés et al. (2017)

Andrés et al. (2017) performed a 2D model of the area between the Barredo and Figaredo shafts (NW Spain) to calibrate the hydrogeological and thermal properties of the mine reservoir, considering the workings and interconnections between them. Three classes of materials where used: the unaltered rock, the mined volume and open voids. In this model, the size of the elements varied from 2.5 around the galleries to 20 m in the unaffected and nearly impermeable rock mass (unconfined isotropic and heterogeneous porous medium). Galleries were assumed to have a rectangular cross section of 8m² and a height of 2.5m, while the shafts were assumed to have a circular section of 25 m². The mined volume (altered material in the zone extending between galleries) were assigned a range of porosity between 2 and 22%, while porosities of 0.1% and 100% were assigned to the unaltered rock mass and galleries. Hydraulic conductivities of 10-7 and 1 m/s were assumed for the unaffected rock mass (Fandos et al., 2004) and the shaft/galleries, respectively. A porosity and hydraulic conductivity of 1% and 10-3 m/s were assigned to the Barredo fault. Ordonez et al. (2012) moreover estimated that the recharge of the Barredo-Figaredo reservoir consisted of a total infiltration representing 23% of the effective rainfall together with a constant water loss from rivers of 5300 m3/day, with the total recharge being equivalent to the average pumping rate. Thermal simulation started after the flooding simulation period, for a constant water level. Variable temperatures representing daily air temperature were set as top boundary condition. A constant flow of 65 mW/m² was set as bottom boundary condition. The temperature of the rock mass at the surface was set to 13°C as an initial condition, while temperature at depth was calculated based on the geothermal gradient, reaching up to 33 °C. 3D models was then developed, requiring simplifications to account for the complexity of the mine galleries. There, galleries at each level were represented by slices of 2.5m height. For each slice, an average porosity of 10% and hydraulic conductivity of 0.5 m/s were assigned to the mined areas where galleries extend, while the mined volume around these zones of galleries and shafts were assigned a porosity of 1% and 100%, respectively. A porosity of 0.1 % was kept for the unaffected rock mass and hydraulic conductivities of 10-7, 2.10-4, and 1 m/s were considered for the unaltered rock mass, the mined volume (zone affected by coal extraction), and the shafts, respectively. In this model, an increased number of nodes were necessary to represent the galleries to avoid convergence errors. Conclusions showed that the temperature of the reinjected water after used in a heating cycle is higher than the average natural recharge water. However, long-term simulations showed that a new equilibrium is set between the cold reinjected water pumped again at 100-200m depth and the surrounding rock below the pump, subsequently leading to a maintain of the abstracted water temperature (Andrés et al., 2017).