# Numerical modelling of flow and heat transport in closed mines. Case study Walsum drainage province in the Ruhr coal-mining area

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**Abstract.** High geothermal potential and multiple mine-water-based geothermal installations in Germany and other countries improve the relevance of detailed studies and modeling of promising sites. In this context, we developed a numerical model of water flow and heat transport in the Walsum mine drainage province in the west of the Ruhr coal-mining area using the available data on geology, mining, water levels, pumping, and the temperatures of deep rocks and mine water. The model was validated by varying the parameters of groundwater recharge and hydraulic conductivity to achieve sufficient consistency with measured inflows and pumping rates from the central pumping facility located in the Walsum 2 shaft. The calculated mine water temperature of 30.3 ºC is close to the average of the measured temperature varied within the range of 29 – 33 ºC during the last years of mine maintenance. Using the numerical model, we evaluated the expected thermal capacity of a hypothetical open-loop circulation system and two closed-loop geothermal systems within the study area. The installation and operation of these systems would enable the generation of a thermal capacity from a few dozen kW to 1 MW sufficient for small-size to mid-size heat consumers with insignificant impact on the high thermal energy potential of the Walsum mine drainage province.

## 1 Introduction

Due to coal deposit exhaustion, mine closures, and the Green Deal implementation in many countries, the coal mining industry is significantly reducing [1 – 5]. Sustainable use of residual energy resources and underground space of abandoned mines are becoming of increasing importance to mitigate the challenges of transition to a more sustainable power sector. They include the transformation and storage of mechanical and thermal energy [6 – 9], and coal gasification and related issues [10 – 13] that enable the utilization of residual resources of coal deposits. Another approach is exploring the geothermal potential of closed

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mines which seems to be more sustainable owing to applying more controllable technologies of mine water and rock heat recovery.

The mine-water-based geothermal applications have been developing in Europe last decades and now many open or closed-loop geothermal systems are in the design phase or under operation in Germany, the UK, Spain, and other countries [14 – 24]. The highest thermal capacity can be achieved in pumping facilities discharging spent water to surface water bodies, but in many cases, borehole heat exchanges (geothermal probes) can be installed in already sealed shafts. For these configurations, there were numerous studies on in-situ investigating the effectiveness of closed-loop systems [25 – 27].

Despite numerous challenges linked with hydrochemistry, hydrodynamics, thermodynamics, and rock stability the proper solutions were found to continue the generation of thermal energy [28]. The positive experience of the long-term operation of such systems demonstrates further prospects of this technology in the countries with the coal industry, which are facing the challenges caused by transforming the power industry and mine closure.

Many mine-water-based geothermal systems were successfully installed in Germany, mostly in the Ruhr coal-mining area with more than 200 closed mines. The hydrodynamical status and mine water level rebound in closed mines in this area and other European coal basins were reviewed in two detailed studies [29, 30].

The geothermal potential of mine water in central pumping facilities and other mining sites in Germany has been assessed in [31] with mapping potential sites and evaluation of expected performance indicators. In these assessments, the power required for operation and maintenance, including pumping and heat losses was not taken into account. An analytical approach to evaluating open-loop system performance was proposed in [32].

The heat extraction by closed-loop systems can be approximately evaluated using the formulas from line source theory [33]. A more detailed approach in [34] enables modelling heat transport considering properly the internal geometry of probes and temperature profiles along the fluid circuit.

The feasibility studies of geothermal sites require regional scale modeling to better define hydrogeological, hydraulic, and mining settings. For large-scale modeling, the finite-element method [35] and the Box model [36, 37] were widely applied to simulate flow and transport in former mining sites in the Ruhr coal-mining area last decades. Along with this, the finite-difference method [38] was also employed to perform hydrodynamic modeling mass and heat transport in mining sites [39, 40]. In the case of hydraulically separated mining sites, an analytical method can be applied [41]. Further detailed investigations may include GIS technologies enhancing the efficiency of heat recovery and distribution [42].

Currently, most numerical modelling software tools solving the same flow and transport equations allow for sufficient gridding of the flow domain with its quite realistic discretization reducing the influence of the grid cell size. Under these circumstances, the availability and accuracy of input data play a much more critical role than the differences between numerical algorithms caused by the discretization way.

The study aims to assess the geothermal potential of a part of the Ruhr coal-mining area in the example of the Walsum drainage province by developing and applying a region-scale numerical model of groundwater and mine water flow and heat transport. This will create the basis for further detailed feasibility studies necessary for geothermal system installations to sustainably recover mine water and rock heat. The numerical model created in the Modflow software allows for grid and parameter refining upon receiving more detailed data on geology, mining, a thermal field, and water level measurements.

## 2 Site characteristics

The mine water level in the Ruhr coal-mining area is maintained by several pumping stations each draining a group of mines after their closure [43]. These groups of mines form drainage provinces with different geothermal potentials depending on local geological and mining conditions. The Walsum drainage province of more than 500 km$^2$ and the biggest depth of 1127 m [44] is drained by the central pumping facility in the Walsum shaft (Fig. 1), which is considered a site with a big potential for mine water heat recovery [31]. The maximum thermal capacity of the drainage facility is estimated at 23.7 MWh assuming a mine water temperature of 29 ºC.

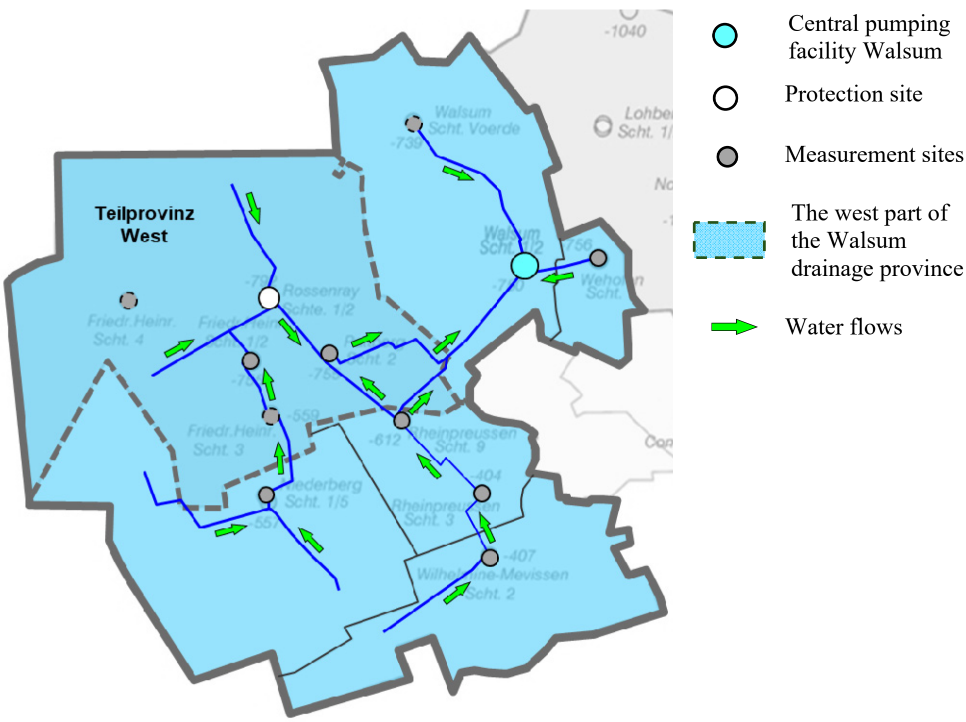


**Fig. 1.** Schematic map of mine water management in the Walsum drainage province according to the data of the operating company Ruhrkohle AG (hereinafter the RAG AG) as of November 2018.

One of the challenges of mine water use in the Ruhr area is its often high mineralization [45]. However, despite the high salt content in the pumped water with electrical conductivity 66,000 – 74,000 µS/cm in the Walsum 2 shaft, there is the possibility of diluting the thermally spent water in the Rhine River with a mean annual flow rate of at least 8000 times higher than the average pumping rate of 254 l/s.

The coal seams in the Walsum province have sunk beneath a thickening overburden inclined by up to 6 degrees. The mine workings deepened by up to 1 km until they reached the mostly flat seams. The thickness of the overburden in the mining area ranges from 340 m in the south to 720 m at the northern boundary. The overburden is formed by the Permian deposits directly above the Carboniferous to the Quaternary sediments near the surface. The host rocks consist of alternating layers of sandstone, sand shale, and shale clay [44, 46].

Mine water flows from the underground mines into the Walsum 2 shaft where it is pumped out to keep the protection water level below -750 m a.s.l. During the period from October, 7$^{th}$ 2020 to October, 7$^{th}$ 2021, the mine water level in the shaft fluctuated from

-760 m to -749.85 m a.s.l. around the mean of -756.07 m a.s.l. During the same period, the temperature of pumped mine water varied from 28.9 ºC to 33.1 ºC with a mean square-root deviation of 1.71 ºC. The average temperature of 30.94 ºC was 2 ºC higher than that used in [31] for calculations. The mine water levels in the Walsum province remained relatively stable fluctuating within a range of up to 10 m (Table 1).

**Table 1.** Mine water levels in the layers and bottoms of the shafts in the Walsum water province (date of the RAG AG).

| Mine[1] | Period of measurements | $h_{mw,a}$, m | $h_{mw,\min}$, m | $h_{mw,\max}$, m | $\Delta h_{mw,sd}$, m |
|---|---|---|---|---|---|
| **Wal 2** | 01.10.20 – 07.10.21 | -756.07 | -760.01 | -749.85 | 2.75 |
| **Ndb 5** | 04.08.20 – 18.08.21 | -556,00 | -556.10 | -555.90 | 0.09 |
| **Whf 1** | 13.07.20 – 27.08.21 | -756.13 | -756.79 | -755.32 | 0.55 |
| **Voerde** | 15.07.20 – 01.07.21 | -746.46 | -749.32 | -744.67 | 1.70 |
| **Ros 2** | 24.09.20 – 07.09.21 | -696.84 | -699.96 | -694.33 | 1.60 |
| **Pat 2** | 18.09.20 – 21.09.21 | -701.61 | -703.89 | -700.01 | 0.94 |
| **WM 2** | 27.09.16 – 17.04.19 | -406.38 | -407,11 | -405.61 | 0.62 |
| **FH 2** | 24.09.20 – 21.09.21 | -699.93 | -702.15 | -697.58 | 1.42 |
| **RhP 3** | 02.04.20 – 07.09.21 | -411.60 | -413.90 | -409.70 | 1.73 |
| **RhP 9** | 06.01.20 – 28.07.21 | -610.30 | -611.60 | -608.90 | 1.22 |

[1]Abbreviations: Wal 2 = Walsum shaft 2, Ndb 5 = Niederberg shaft 5, Whf 1 = Wehofen shaft 1, Ros 2 = Rossenray shaft 2, Pat 2 = Pattberg shaft 2, WM 2 = Wilhelmine-Mevissen shaft 2, FH 2 = Friedrich Heinrich shaft 2, RhP 3 = Rheinpreussen shaft 3, RhP 9 = Rheinpreussen shaft 9.

A more detailed analysis of mine water monitoring demonstrates stable or slowly sinking water levels in shafts with higher or medium water tables such as Rheinpreussen shaft 3, Wilhelmine-Mevissen shaft 2, Niederberg 5, Rheinpreussen shaft 9, stable mine water levels in the shafts with the lowest water tables (Voerde, Wehofen 1, Walsum), and raising mine water levels in the shafts with the water level that was 40 – 50 m higher than the level in the Walsum 2 shaft (Pattberg 2, Friedrich Heinrich shaft 2, Rossenray shaft 2). The rate of mine water level rebound varies from 3.4 mm/d in the mine Pattberg 2 to 11.8 mm/d in the mine Rossenray 2. The statistically obtained average values were used for interpolating the levels of mine water and groundwater.

The deep rock temperature and, consequently, the geothermal heat flux in the Ruhr area slightly increases from south to north with local zones of elevated temperature measured in the Lippe and Emscher valley regions west of Recklinghausen [47]. The increase in soil temperature relative to the temperature of the neutral layer below the surface of 10 ºC is 148 – 167 ºC, so the range of variation is below 7%. Based on these data we calculated the temperature of rocks in the flow domain.

## 3 Data and methods

The area of the Walsum drainage province is very heterogeneous so water flow and heat transport should be simulated numerically. Using the Visual Modflow software [38], we covered the area of the Walsum province with the finite-difference grid to perform numerical modelling of water and heat transport. The grid of cells each 250 m × 250 m is sufficient for regional modelling but must be refined further for local models of single geothermal systems using detailed underground geometry data. The flow domain was structured by 6 calculation layers with the deepest layer in Carboniferous deposits (Fig. 2). Water transport in overlying layers influences mine water flow in the Carboniferous layer by groundwater recharge, which is close to the conductivity of overlying clays. The elevations of the layers mostly deepening to the north were defined based on the stratigraphic columns of all shafts.

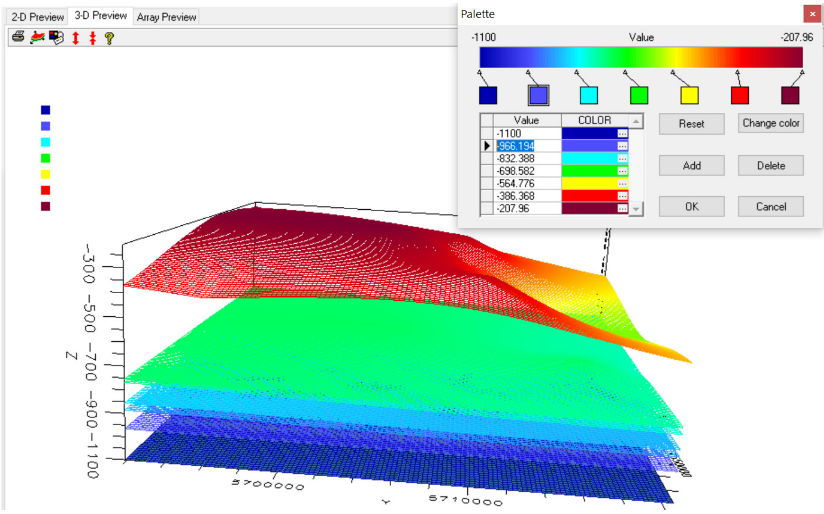


**Fig. 2.** Surfaces of the model layers. View from the east side.

The hydraulic conductivity and porosity of rocks affected by mining operations were set to previous investigations [46]. The data on the residual void volume were taken from open sources on mining activities including [44], whereas spatial locations of underground workings were provided by mining engineers. The available data on extracted coal and the volume of mined-out rocks allowed us to derive the anthropogenic porosity of 0.015 – 0.02 in mining zones. The conductivity and capacity parameters considering the effects of mining-induced heterogeneity were defined depending on the locations of workings.

The so-called general head boundary condition on the outer boundary of the flow domain with an almost undisturbed groundwater level was defined assuming a low hydraulic connection with neighboring underground areas and other mining drainage provinces. The recharge of the Carboniferous layer was evaluated based on the pumping rate at the central drainage facility of about 8 million m$^3$/a (21.917 m$^3$/d) and the conductivity of the undisturbed overlying rocks $k_{f,\min}$ of $3 \cdot 10^{-10}$ m/s. With the conductivity $k_{f,\min}$ of $4.85 \cdot 10^{-10}$ m/s the recharge inflow reaches the outflow rate, but one should include also the deep inflow in the water balance. In modelling, we varied the recharge from 10 to 12 mm/a, which is equivalent to the range 14.247 – 17.096 m$^3$/d of inflow.

The internal flow boundary conditions for the channels transporting drained water as drains. In this way, the Modflow software enables simulating the hydraulic effect of underground waterways through all mines at the 4$^{th}$ and 5$^{th}$ levels to the Walsum 2 shaft. With such a boundary condition, the mine water is theoretically removed from the workings once it enters the channels. In reality, mine water flow in channels on the bottom of workings takes some time that can be evaluated from the pumping rate, the cross-sectional area, and the waterway length. The estimated flow velocity in the hydraulic connections is around 100 – 400 m/d which correlates with experimental measurements [48] comparable so that mine water from southern areas of the water province can reach the pumping facility after 1 – 3 months. This effect should be accounted for short-term assessments but is uninfluential for long-term predictions of flow and heat transport.

The initial groundwater temperature was evaluated according to the vertical distribution of the rock temperature depending on model layer elevations and the geothermal gradient.

Geologically, the layers gradually sink towards the north, thus, the mine water temperature is increasing in the same direction, reaching the maximums at the shafts Walsum 1/2, Voerde, and Wehofen 1 with the lowest water levels in the north.

# 4 Results and discussion

The model was validated by minimizing the difference between the calculated and measured values of outflow. The mine water levels are available in individual shafts only, but these data cannot be directly compared with the calculated groundwater head at the same points. Underground workings occupy a small part of the volume of a grid cell (up to 5%), whereby the calculated level applies to the entire grid cell. The results of the groundwater measurements in the Walsum drainage province are not available, so the total discharge rate of the drain $Q_{dr,tot}$ was the main parameter for balancing water flows.

Since the water flow from remote areas to the pumping facility takes some time, mine water is slightly heated this time by the deep geothermal flux, which can be estimated as

$$\Delta T_{mw,gth} = \frac{E_{gth}}{V_{mw} C_{mw} \rho_{mw}}, \tag{1}$$

where $E_{gth}$ is the heat energy that the flowing water gains on its way to the pump shaft; $V_{mw}$ the volume of mine water; $C_{mw}$, $\rho_{mw}$ the specific heat capacity and density of mine water. For the water transport period in warmer rocks during 100 – 300 days, the temperature can rise by 0.5 ºC. The temperature of the mine water in the Walsum 2 shaft was calculated as the average of the groundwater temperature in the shafts, with correcting its value depending on layer elevations.

We calculated the groundwater level for the steady-state regime first, as it corresponds to the current status with the almost stable water level in shafts. Then, the unsteady heat transport was simulated for 25 years. The results of inverse modelling with variations of conductivity of Carboniferous deposits and recharge (Table 2) are summarized in Table 3, where the following notations are applied: $k_{f,x}$, $k_{f,y}$, $k_{f,z}$ are the conductivity along the axes $O_x$, $O_y$, $O_z$; $\alpha_{kf}$ the multiplication factor to vary the conductivity ($\alpha_{kf} = 1$ means no deviation, $\alpha_{kf} = 0{,}9$ means reduction of all $k_f$ values by 10%, $\alpha_{kf} = 1.1$ means increasing all values by 10%; $S_s$ is the specific storage; $S_y$ the specific yield; $n_{eff}$ is effective porosity; $n_t$ is total porosity; $w_{inf}$ the groundwater recharge; $Q_{inf}$ is infiltration water inflow; $Q_{gw}$ the deep groundwater inflow; $Q_{dr}$ the total drainage from the mining area collected in the Walsum 2 shaft; $\Delta Q_{tot}$ the deviation between the calculated and measured total discharges; $\Delta\bar{Q}_{tot}$ is the deviation $\Delta Q_{tot}$ related to the measured average discharge of 21.917 m$^3$/d; $T_{mw,a}$ is the average temperature of mine water pumped from the Walsum 2 shaft.

**Table 2.** Hydraulic conductivity and porosity of Carboniferous sediments identified by inverse modelling for the Walsum mine drainage province.

| Rocks | $k_{f,x}$, m/s | $k_{f,y}$, m/s | $k_{f,z}$, m/s | $S_s$, 1/m | $S_y$ | $n_{eff}$ | $n_t$ |
|---|---|---|---|---|---|---|---|
| Untouched | $1.2\cdot10^{-7}$ | $1.2\cdot10^{-7}$ | $0.75\cdot10^{-7}$ | $1.0\cdot10^{-6}$ | 0.01 | 0,01 | 0,02 |
| Disturbed | $2.9\cdot10^{-7}$ | $2.9\cdot10^{-7}$ | $2.0\cdot10^{-7}$ | $5.0\cdot10^{-6}$ | 0.02 – 0.03 | $0.025 \pm 0.01$ | $0.035 \pm 0.01$ |

Variant No. 1 allows to minimize the deviation between calculated and measured inflows, the other variants with variations of conductivity and recharge up to 10% demonstrate a higher deviation of up to 4%. Lower recharge or higher permeability increases the share of deep inflow in the water balance.

**Table 3.** Total water balance evaluation for the Walsum mine drainage province.

| Variant | $w_{inf}$, mm/a | $\alpha_{kf}$ | $Q_{inf} + Q_{gw}$, m$^3$/d | $Q_{dr}$, m$^3$/d | $\Delta Q_{tot}$, m$^3$/d | $\Delta\bar{Q}_{tot}$, % | $T_{mw}$, ºC |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 1 | 21.913 | 21.910 | -7.8 | 0.04 | 30.302 |
| 2 | 9 | 1 | 21.081 | 21.078 | -839.8 | 3.83 | 30.297 |
| 3 | 11 | 1 | 22.748 | 22.742 | 824.2 | 3.76 | 30.307 |
| 4 | 10 | 0.9 | 21.008 | 21.005 | -912.8 | 4.16 | 30.296 |
| 5 | 10 | 1.1 | 22.779 | 22.773 | 855.2 | 3.90 | 30.308 |

The influence of these parameters on the mine water temperature does not exceed 0.1 ºC. Mine water flows from different parts of the Walsum drainage province where the temperature varies within the evaluated interval of 26.5 – 35.5 ºC, so changing inflows of groundwater of different temperatures may have opposite effects on the temperature of pumped mine water. The calculated mine water temperature of 30.3 ºC falls in the measured range around the mean value 30.94 ºC. Thus, with the data available the model calculates the key parameters of flow and heat transport close to measured ones. The calculated groundwater flow and temperature maps for variant No. 1 from Table 3 demonstrate predominantly north-oriented flow and the rising temperature to the north direction (Figs. 3 and 4).

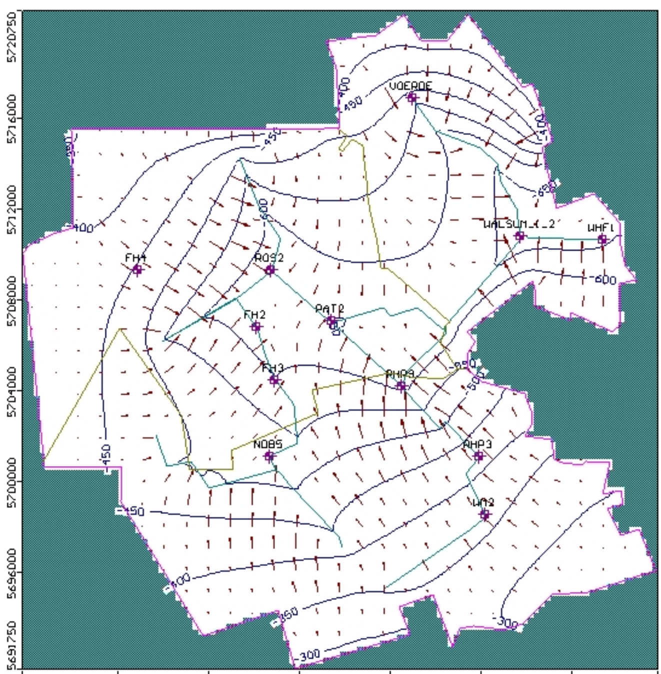


**Fig. 3.** Flow pattern in the 4th model layer of the Walsum mine drainage province. Groundwater levels are denoted with dark-blue lines, underground waterways with grey-green lines, flow directions with arrows, and shafts with lilac markers.

The maximum thermal capacity $P_{th,\max}$ of 23.7 MW evaluated in [31] at the average mine water temperature $T_{mw}$ of 29 ºC, and the theoretical thermal energy potential $E_{th,\max}$ of 207.6 GWh/a can be updated based on the modelling results and measurements in 2020 – 2021. The maximum thermal capacity $P_{th,\max}$ and the energy potential are 7.6% higher and are estimated as $25.52 \pm 2.1$ MW, and $E_{th,\max} = 223.6 \pm 18.3$ GWh/a, respectively. The energy demand of local consumers near the Walsum pumping facility evaluated at 140 MWh/a takes up a very small share of the theoretical potential.

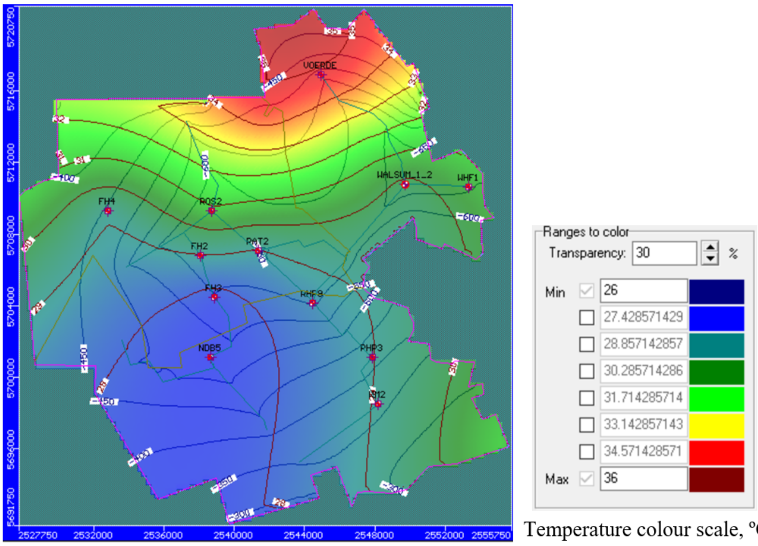


**Fig. 4.** Calculated mine water level and temperature in the Walsum water province in the 4th model layer. Groundwater level is shown with dark-blue lines, underground waterways with grey-green lines, groundwater temperature with brown lines, and shafts with red markers.

Therefore, it is possible to use the available thermal energy potential of the Walsum mine drainage province at other locations or shafts. Based on the analysis of geotechnical conditions of the shafts in this area and the availability of local heat consumers the following options can be studied in more detail:

1) the closed-loop systems for mine water heat recovery at the shafts Rossenray 2 and Friedrich Heinrich 4;

2) the open-loop circulation system at Friedrich Heinrich shafts 1(2).

These locations are in the city of Kamp-Lintfort with around 38.000 inhabitants. According to the available data, the other shafts are mostly sealed, so that only the backfilled columns are available for installing closed-loop systems.

The energy potential of the closed-loop systems at the shafts Rossenray 2 and Friedrich Heinrich 4 is evaluated using the method proposed in [49, 50]. For this purpose, the measured mine water level (see Table 1) and the deepest levels in the shafts were applied, and the mine water temperature was evaluated by modelling (Table 4).

**Table 4.** Mine water levels in the layers and bottoms of the shafts in the Walsum mine drainage province (data on the shafts provided by the RAG AG).

| **Mine**[1] | **Ndb 5** | **Whf 1** | **Voerde** | **Ros 2** | **Pat 2** | **WM 2** | **FH 2** | **RhP 3** | **RhP 9** |
|---|---|---|---|---|---|---|---|---|---|
| $h_{mw,a}$, m | -556.03 | -756.13 | -746.46 | -696.84 | -701.61 | -406.38 | -699.93 | -411.64 | -610.27 |
| $h_d$, m | -993.2[2] | -925[3] | -1027 | -897 | -901.8 | -901.8[4] | -931.4 | -901.8[4] | -901.8[4] |
| $T_{mw,a}$, °C | 26.93 | 29.89 | 34.79 | 30.19 | 28.36 | 28.26 | 28.33 | 28.36 | 27.96 |

[1]Abbreviations see below Table 1, $h_d$ is the deepest point in the shaft, $T_{mw,av}$ the average mine water temperature in the interval $h_d < z < h_{mw,a}$.

The specific heat extraction rate of the coaxial probes is evaluated at 121 W/m and 115.7 W/m for the shafts Rossenray 2 and Friedrich Heinrich 4 proportional to the difference of 6 ºC between the calculated temperature and the cooling temperature in the heat pump. Taking into account the thickness of the flooded zone, the thermal output of the probes is evaluated at 24.19 kW and 19.66 kW, respectively. Mine water heat recovery was simulated in the Modflow software with two point sources of the same flow rate, where one source pumps out warmer water from the lowest level in the 4$^{th}$ layer, and the other source discharges colder water into the grid cell above in the 3$^{rd}$ layer. In this approach one can simulate hydraulically neutral heat extraction, calculating the thermal capacity and performance indicators of the system from the temperature difference.

The expected thermal impact of geothermal probes is local and small; the temperature in the grid cells with the shafts almost coincides with the average temperature in the flooded zone of the shaft. The groundwater temperature near the shafts after 25 years of operation is expected to drop by 2.53 ºC and 1.89 ºC. However, this would have a neglectable effect of below 0.0001 ºC on the cooling of mine water in the Walsum pumping shaft. The thermal energy potential of geothermal systems at shafts Rossenray 2 and Friedrich Heinrich 4 is evaluated at 211.9 MWh/a and 172.2 MWh/a, respectively. These assessments should be refined in further detailed studies during project planning, taking into account underground working geometry and hydraulic flows.

Considering the possible long-term operation of an open geothermal system at Friedrich Heinrich shafts 1 (2), one should minimize the cooling effect of the return flow of thermally spent water. To do this, the cooled water can be drained through the underground hydraulic connection to the northwest from the Friedrich Heinrich shaft 1 or 2, where the mine water flows to the Walsum 2 shaft. In this way, it is possible to pump warm mine water from the southern parts of the mine drainage province with a relatively stable temperature.

The proposed approach is simulated as follows. The water withdrawal from Friedrich Heinrich shaft 1(2) is modeled as the point source with a negative flow rate evaluated based on the water balance of the shaft catchment area to the south. The calculated mine water flow through this shaft from the south reaches 3417.7 m$^3$/d so the circulation flow rate of 1000 m$^3$/d looks realistic. The temperature of pumped mine water is defined as the calculated temperature at the Friedrich Heinrich shaft 1(2). Based on these data, we can derive the thermal capacity of the open-loop circulation system.

The thermal effect of cooled water return to underground workings was simulated with the series of point sources along the underground hydraulic connection. The calculated groundwater temperature at the shafts Friedrich Heinrich 1(2) and Rossenray 2 gradually decreases by 1.04 ºC and 0.37 ºC respectively, and the maximum thermal capacity reduces by 4.5% due to an enhanced inflow of cooler water upstream of the catchment area (Fig. 5).

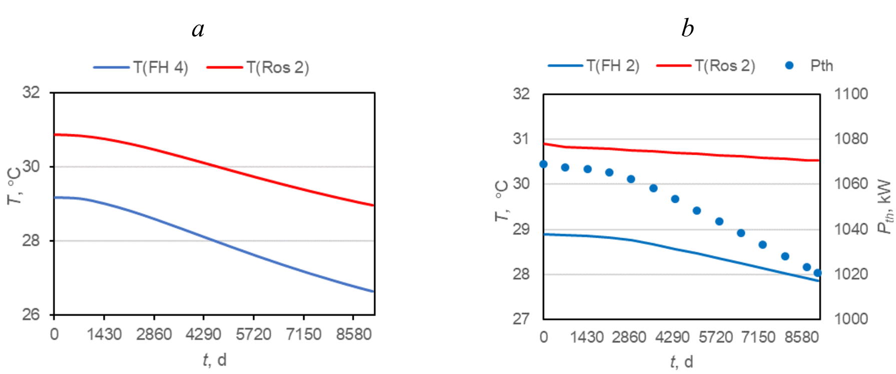


**Fig. 5.** Expected temperature and thermal capacity of geothermal systems in potential locations: (a) the temperature in the 3$^{rd}$ model layer near the closed-loop systems at the Friedrich Heinrich shaft 4 and Rossenray 2; (b) the mine water temperature in the 3$^{rd}$ model layer and thermal capacity of an open-loop circulation system at the Friedrich Heinrich Shaft 2.

Cooling of mine water in the Walsum 2 pumping facility due to mine water heat recovery in the potential geothermal systems can be calculated using the equation of mixing. The mine water temperature at the Walsum 2 shaft is expected to decrease to 29.2 °C, which is 1.1 ºC less than without using the circulation system. This may cause the reduction of the maximum thermal capacity at the Walsum pumping facility $P_{th,\max}$ from 24.87 MW to 23.75 MW, and theoretical thermal energy potential $E_{th,\max}$ from 217.8 GWh/a to 208.1 GWh/a. Taking into account the evaluated demands of local heat consumers near the Walsum 2 shaft, this reduction does not look critical. Along with this, the thermal impact of the open-loop system may spread up to 4 – 5 km downstream compared to the area influenced by closed-loop systems.

## 5 Conclusions

In this study, we developed a numerical model of water and heat transport to assess the potential of mine water heat recovery in the Walsum mine drainage province considered very promising in terms of energy use of mine water. The created model covers an area of more than 500 km$^2$ and consists of 6 layers slightly deepening to the north direction. The model was validated based on the available data on mine water levels, discharge at the central pumping facility, and mine water temperature. Regarding data uncertainty, we identified the flow properties of Carboniferous deposits by varying conductivity of rocks and recharge.

The calculated mine water temperature of 30.3 ºC falls in the interval of measurements from 28.9 ºC to 33.1 ºC with an average of 30.94 ºC and a standard deviation of 1.71 ºC. Water inflows and outflows were balanced at 0.04% deviation. The maximum thermal capacity and energy potential of the Walsum 2 pumping facility are evaluated at 25.52 ± 2.1 MW, and 223.6 ± 18.3 GWh/a, respectively. These indicators are much higher than the thermal energy demand of local consumers estimated at 140 MWh/a.

Using modelling, we calculated the expected performance of hypothetical geothermal systems in the studied area. They include an open-loop system at the Friedrich Heinrich shaft 1(2) and closed-loop systems in the flooded part of the shafts Rossenray 2 and Friedrich Heinrich 4. With an achievable flow rate of 1000 m$^3$/d at the Friedrich Heinrich shaft 1(2), the heat capacity of the open-loop system may exceed 1 MW, which could cover the needs of mid-size heat consumers. Installing the closed-loop systems at the shafts Rossenray 2 and Friedrich Heinrich 4 would enable reaching the thermal output of 20 – 24 kW sufficient for small-size heat consumers.

The model calculations demonstrate that heat extraction at individual locations in the catchment area of the Walsum 2 pumping facility does not have a significant influence on the thermal energy potential of the drainage province. This preliminary conclusion should be refined with more precise and detailed data before the installation of geothermal systems. Further studies should pay more attention to the underground geometry, rock heterogeneity, and hydraulic interactions on outer boundaries.

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